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# SKIN FRICTION MEASUREMENTS AT A MACH NUMBER OF THREE AND MOMENTUM THICKNESS REYNOLDS NUMBERS UP TO A HALF MILLION

Anthony W. Fiore
Aeromechanics Division



September 1980

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Anthony W. Fiore

ANTHONY W. FIORE
Project Engineer
High Speed Aerodynamics Group

Arnold G. Crowder

ARNOLD G. CROWDER, MAJ, USAF
Act'g Chief, High Speed Aero Perf. Br.
Aeromechanics Division

*FOR THE COMMANDER*

Peter J. Butkewicz

PETER J. BUTKEWICZ
COLONEL, USAF
Chief, Aeromechanics Division

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Surface shear stress measurements were made in the Flight Dynamics Laboratory's M=3 High Reynolds Number wind tunnel, ~~located in Bldg. 450, Area B of Wright-Patterson~~ Air Force ~~Base, Ohio~~. The primary purpose of this research was to make shear stress measurements at very high Reynolds numbers for near adiabatic wall and zero pressure gradient conditions. The results are presented as the local skin friction coefficient versus both the momentum thickness and the length Reynolds number. The investigation was conducted on the

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nozzle wall at a nominal Mach number of three over the Reynolds number range of $2 \times 10^4 \leq R_{e_\theta} \leq 50 \times 10^4$. The surface shear stress was measured with a balance. The resulting skin friction coefficients were verified by simultaneous measurements made with a Preston tube. The skin friction coefficient was also calculated using the Von Karman integral method. They were then compared with the experimental results of Matting et al., and Moore-Harkness along with the theories of Van Driest, Spalding-Chi, Wilson, and Shang et al.

The skin friction coefficients obtained by these methods agree with the results of Matting et al., in the Reynolds number range of $2 \times 10^4 \leq R_{e_\theta} \leq 18 \times 10^4$ and with the Moore-Harkness data in the range of Reynolds number given by $18 \times 10^4 \leq R_{e_\theta} \leq 50 \times 10^4$. These measurements also agree reasonably well with the theories of Van Driest, Spalding-Chi, Wilson, and Shang.

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## FOREWORD

This report was prepared by Dr. Anthony W. Fiore of the Aeromechanics Division of the Flight Dynamics Laboratory (AFWAL/FIMG), Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The research was conducted under Work Unit Number 2307N424 entitled "Viscous and Interacting Flow Fields about Flight Vehicles". This report contains the results of an investigation undertaken to obtain skin friction coefficients at very high Reynolds numbers in a supersonic boundary layer. The research was conducted at a nominal Mach number of three for near adiabatic wall and zero pressure gradient conditions. This particular effort concerns itself with the measurements of surface shear stress from which the skin friction coefficient was obtained. The original experiments were performed between April 1974 and June 1978. They were conducted on the tunnel nozzle wall at a nominal Mach number of three, in the range of momentum thickness Reynolds numbers extending from $2 \times 10^4$ to approximately $50 \times 10^4$.

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## LIST OF SYMBOLS

$(C_f)_G$ = Skin Friction Coefficient measured with the Balance

$(C_f)_A$ = Skin Friction Coefficient obtained with the Preston Tube and Equation 18

$(C_f)_{HK}$ = Skin Friction Coefficient obtained with the Preston Tube and Equation 17

$(C_f)_Y$ = Skin Friction Coefficient obtained with the Preston Tube and Equation 16

$C_f$ or $(C_f)_p$ = Skin Friction Coefficient defined by Equation 21

$(C_f)_{VK}$ = Skin Friction Coefficient obtained by the Von Karman Integral Method (Equation 22)

$A_1$ = Van Driest function defined by Equation A.2

$B_1$ = Van Driest function defined by Equation A.3

$a_o$ = Spalding-Chi temperature ratio $(T_w/T_e)$

$b_o$ = Spalding-Chi function defined by Equation A.11

$c_o$ = Spalding-Chi Mach number function defined by Equation A.12

$F$ = The Shear Force measured with the balance in lbs

$F_1$ = The Allen function defined by Equation 20

$F_c$ = Spalding-Chi multiplying factor defined by Equation A.13

$F_{R\theta}$ = Spalding-Chi multiplying factor defined by Equation A.14

$\ell$ = Reference length in feet

$M$ = Mach number

$P$ = Pressure in lbs/in$^2$

$q = \frac{\gamma}{2} pM^2$ = Dynamic Pressure in lbs/in$^2$

$R_e/\ell = \rho U/\mu$ = Unit Reynolds number in ft$^{-1}$

$R_{e_d} = \dfrac{\rho_e U_e d}{\mu_e}$ = Preston Tube Reynolds number

$R^*_{e_d} = \dfrac{\rho^* U_e d}{\mu^*}$ = Preston Tube reference temperature Reynolds number

LIST OF SYMBOLS (Cont'd)

| | |
|---|---|
| $R_{e_x}$ | = Length Reynolds number |
| $R_{e_\theta}$ | = Local momentum thickness Reynolds number |
| $\bar{R}_{e_\theta}$ | = Incompressible momentum thickness Reynolds number defined by Equation A.4 |
| T | = Temperature in degree Rankine |
| U | = Velocity in ft/sec |
| x | = Distance from the tunnel throat to the probing station in inches |
| $\alpha$ | = Wilson's function defined by Equation A.6 |
| $\beta$ | = Wilson's viscosity ratio function defined by Equation A.7 |
| $\sigma$ | = Wilson's Mach number function defined by Equation A.8 |
| $\delta$ | = Boundary Layer thickness in inches |
| $\delta^*$ | = Boundary Layer displacement thickness in inches |
| $\theta$ | = Boundary Layer momentum thickness in inches |
| $d\theta/dx$ | = Variation in momentum thickness with the distance "x" as defined by Equation 23 |
| $\rho$ | = Density in slugs/ft$^3$ or lbs sec$^2$/ft$^4$ |
| $\mu$ | = Coefficient of viscosity in lbs sec/ft$^2$ |
| $\nu = \mu/\rho$ | = Kinematic viscosity in ft$^2$/sec |
| $\tau_w$ | = Measured wall shear stress in lbs/in$^2$ |

Superscripts

| | |
|---|---|
| * | = Values based on Sommer and Short reference temperature method |

## LIST OF SYMBOLS (Cont'd)

Subscripts

| | |
|---|---|
| e | = Boundary Layer edge conditions |
| g or G | = Conditions based on force balance measurements |
| O | = Tunnel reservoir conditions |
| P | = Conditions based on Preston Tube measurements |
| S | = Shang's Theory |
| SC | = Spalding-Chi Theory |
| t | = Local total (or stagnation) conditions |
| VD | = Van Driest Theory |
| VK | = Von Karman Integral Method |
| W | = Wall conditions and/or Wilson's Theory |
| aw | = Adiabatic wall conditions |

Constants

| | |
|---|---|
| A | = Cross-sectional area of the floating element of the shear stress balance given as 0.10752 $in^2$ |
| a | = Constant in Equation 18 taken as 0.01659 |
| b | = Constant in Equation 18 taken as 0.7665 |
| c | = Constant in Equation 18 taken as 0.4681 |
| d | = Preston Tube outside diameter (0.062 inches) |
| R | = Gas constant for air (1715 $ft^2/sec^2 {}^\circ R$) |
| $\gamma$ | = Ratio of specific heats for air (1.40) |
| r | = Turbulent recovery factor taken as 0.89 |

# SECTION I

# INTRODUCTION

With the advent of the world energy crisis, it is rapidly becoming necessary to find methods for decreasing the total drag of flight vehicles in order to either decrease the fuel consumption for a given flight range or to increase the range for a prescribed fuel load. In supersonic flight approximately twenty percent of the total drag consists of skin friction drag. Because of its importance, it becomes necessary to obtain a more accurate estimate of this portion of the total drag. To date the only skin friction data available at very high Reynolds numbers are the few points of Moore and Harkness.(1) The purpose of this investigation was to make measurements of the supersonic skin friction coefficients over a large range of Reynolds numbers corresponding to those encountered by future very large flight vehicles or vehicles designed to fly at low altitudes.

Research was carried out on the contoured nozzle wall of the Flight Dynamics Laboratory's high Reynolds number wind tunnel. Surface shear stress measurements, leading to local skin friction coefficients, were made at a nominal Mach number of three over the momentum thickness Reynolds number range extending from $2 \times 10^4$ to $50 \times 10^4$.

This corresponds to a length Reynolds number, based on the assumption that transition occurs at the tunnel throat, ranging from $10^7$ to approximately $10^9$.

The surface shear stresses presented in this report were measured with a balance, measurements were also made with a Preston tube. The skin friction coefficient was also calculated using the Von Karman integral method. These experiments were conducted at near adiabatic wall conditions in the absence of a pressure gradient.

# SECTION II

# EXPERIMENTAL APPARATUS

## 1. THE WIND TUNNEL

The Flight Dynamics Laboratory's Mach Three High Reynolds Number Wind Tunnel is a blowdown facility with an 8.2 x 8 inch closed test section whose upper and lower walls are contoured. It operates at stagnation pressures of 50 to 600 psia. Since the facility does not have a temperature control system, the stagnation temperature is slightly below ambient temperature resulting from the Joule-Thompson effect. At these conditions the facility is capable of operation in the range of freestream unit Reynolds number extending from $10^7$ to approximately $10^8$ per foot. It is designed to run continuously for a maximum period of 10 minutes. Run duration during this investigation averaged about 30 seconds. Further details on operating procedures and calibration of this wind tunnel are available in Reference 2.

## 2. INSTRUMENTATION

### a. Surface Shear Stress Balance and the Balance Retraction Mechanism

The surface shear stress was measured directly with a floating element balance shown in Figure 1. It was manufactured by the Kistler Instrumentation Company. It is a self-sealed unit with a flat surface permitting flush mounting in the tunnel wall. The floating element is 0.37 inches in diameter and has a peripheral gap of 0.003 inches. The balance is self-nulling to the center position and is statically balanced about all three axis.

Prior to installation in the tunnel, the balance was calibrated by applying known weights. Before and after each run the calibration was constantly checked with a self-calibration coil contained within the balance housing. The readout and electronic calibration control is also shown in Figure 1.

Primary concern was the possible destruction of the balance when exposed to tunnel starting-and-stopping-loads encountered when the tunnel shock wave passes over the balance's floating element. In order to protect the balance from failure, the injection system shown in Figure 2 was developed. Prior to tunnel operation, the balance is retracted within the housing, whose environment is at ambient conditions. The shutter is closed and pressure is placed against it with a pneumatic cylinder permitting the balance to be sealed within its housing. The housing unit is then evacuated to the anticipated freestream static pressure. With the balance protected in this manner, the tunnel is started. Once the starting shock has passed the probing station and the proper freestream test conditions have been established, the pneumatic pressure is released. The shutter automatically lifts and rotates to the open position exposing the balance to the test environment.

It is then lowered into position flush with the tunnel surface and the wall shear stress is measured. The balance is then retracted into the housing and the shutter is closed. The housing unit is once again returned to ambient conditions and the tunnel is shut down. The injection system is fully automatic and was designed so the injection (or retraction) cycle can be completed in approximately five seconds.

b. The Preston Tubes

Two Preston tubes and their related wall static pressure and temperature instrumentation were used to provide a second method for measuring the wall shear stress. The general arrangement of these tubes is shown in Figure 2 while the detailed design is shown in Figure 3. They consisted of cylindrical pitot pressure tubes placed tangent to the surface. They were constructed from #304 annealed stainless steel tubing with outside and inside diameters of 0.062 and 0.0472 inches respectively. The streamwise length of these pitot tubes was 0.125 inches long. Provided the Preston tubes have been properly calibrated, the local surface shear stress is obtained from the measurements of wall static pressure, wall temperature, and the Preston tube total pressure (References 3, 4, and 5). The Preston tube outside diameter to boundary layer thickness ratio varied from 0.041 to approximately 0.124 depending upon the local Reynolds number.

A brief error analysis of the skin friction coefficients obtained by both the balance technique and the Preston tube method are presented in Appendix B of this report.

# SECTION III

## TEST PROCEDURE

This investigation was conducted at a nominal Mach number of three and at momentum thickness Reynolds numbers varying from $2 \times 10^4$ to $50 \times 10^4$ for near adiabatic wall and zero pressure gradient conditions. The Reynolds number was changed by two methods; namely, by changing the tunnel reservoir pressure from 50 psia to approximately 560 psia for a given probing station and by testing at eight different longitudinal stations for a constant tunnel reservoir pressure. The eight station locations are shown in Figure 4.

The tunnel was operated manually rather than in the automatic mode. This operational procedure permitted more time for starting load adjustment as compared to an impulsive tunnel start common to the automatic mode. All the data was recorded as a function of time on a multi-channel oscillograph. The recorded data were the tunnel reservoir pressure and temperature, wall static pressure, wall temperature, the Preston tube total pressure, and the surface shear stress measured with the balance. The instantaneous values of these parameters were used in the data reduction process.

# SECTION IV

# DATA REDUCTION

The data reduction procedure described in the following paragraphs involves only the calculations necessary to convert the experimental measurements to a form consistent with boundary layer standard parameters such as skin friction coefficients, momentum thickness Reynolds numbers, and other various parameters used in the different theories.

Since the boundary layer is assumed to be a constant pressure boundary layer, the edge Mach number is calculated from the energy equation:

$$M_e = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P_o}{P_w}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{1}$$

The edge temperature, density, and velocity are computed from:

$$T_e = T_o/(1 + \frac{\gamma-1}{2} M_e^2) \tag{2}$$

$$\rho_e = 144 \frac{P_w}{RT_e} \tag{3}$$

and

$$U_e = M_e \sqrt{\gamma RT_e} \tag{4}$$

The viscosity at the edge of the boundary layer was calculated from Keyes's[13] equation written in the form:

$$\mu_e = 2.32 \times 10^{-8} \sqrt{T_e} \Bigg/ \left[1 + \frac{220}{T_e \, (10^{9/T_e})}\right] \tag{5}$$

where the edge temperature, $T_e$, was obtained from Equation 2. The unit Reynolds number was calculated from the basic definition:

$$\frac{R_e}{\ell} = \frac{\rho_e U_e}{\mu_e} \tag{6}$$

while the length and momentum thickness Reynolds numbers are obtained from:

$$R_{e_x} = \left(\frac{R_e}{\ell}\right) \left(\frac{X}{12}\right) \tag{7}$$

and

$$R_{e_\theta} = \left(\frac{R_e}{\ell}\right) \left(\frac{\theta}{12}\right) \tag{8}$$

From nozzle boundary layer measurements made at conditions of M=3 and near adiabatic wall conditions Fiore[7] found that the momentum thickness in Equation 8 can be calculated from the empirical expression:

$$\frac{\theta}{x} = 4.5133 \times 10^{-4} \frac{M_e^{1.1109}}{R_{e_x}^{0.0507}} \tag{9}$$

The skin friction coefficient obtained with the balance was calculated from the measured surface shear stress and the dynamic pressure at the edge of the boundary layer as follows:

$$(C_f)_g = \frac{\tau_w}{q_e} = \frac{(F/A)}{\frac{\gamma}{2} P_e M_e^2} \tag{10}$$

An empirical relationship was required to reduce the Preston tube measurements to $C_f$ values. In this experiment, the Sommer and Short[8] reference temperature method was used, this relationship is:

$$\frac{T^*}{T_e} = \frac{\rho_e}{\rho^*} = (0.55 + 0.035 M_e^2 + 0.45 \frac{T_w}{T_e}) \tag{11}$$

from which the quantity T* was obtained.

The density corresponding to this reference temperature simply becomes:

$$\rho^* = 144 \frac{P_w}{RT^*} \qquad (12)$$

while the corresponding viscosity is:

$$\mu^* = 2.32 \times 10^{-8} \sqrt{T^*} \Big/ \left[ 1 + \frac{220}{T^* \left(10^{9/T^*}\right)} \right] \qquad (13)$$

The Preston tube Reynolds number in the reference temperature form is simply:

$$R^*_{e_d} = \frac{\rho^* U_e d}{12 \mu^*} \qquad (14)$$

where "d" is the Preston tube outside diameter in inches. The Preston tube Mach number, $M_p$, was calculated by iterating the Rayleigh pitot formula:

$$\frac{P_t}{P_w} = \left[ \frac{\gamma+1}{2} M_p^{\,2} \right]^{\frac{\gamma}{\gamma-1}} \left[ \frac{(\gamma+1)}{2\gamma M_p^{\,2} - (\gamma-1)} \right]^{\frac{1}{\gamma-1}} \qquad (15)$$

where $P_t$ is the measured Preston tube total pressure and $P_w$ is the corresponding wall static pressure.

The skin friction coefficient was calculated using the R.M.S. value of three empirical equations. They are the Yanta form[4]

$$(C_f)_Y = 0.0736 \frac{(M_p/M_e)^{1.71}}{\left[ \left(\frac{\rho_e}{\rho^*}\right) R^*_{e_d}{}^{2} \right]^{0.144}} \qquad (16)$$

the Hopkins and Keener expression [3]

$$(C_f)_{HK} = 0.0522 \frac{\left(\frac{M_p}{M_e}\right)^{1.75}}{\left[\left(\frac{\rho_e}{\rho^*}\right) R^*_{e_d}{}^2\right]^{0.125}} \tag{17}$$

and Allen's original form taken from Reference 5 as

$$(C_f)_A = \left(\frac{\rho_e}{\rho^*}\right)\left\{\frac{1}{\left(\frac{\mu_e}{\mu^*}\right) R_{e_d}}\left[10^{\left(a \log^2 F_1 + b \log F_1 - c\right)}\right]\right\}^2 \tag{18}$$

where a = 0.01659, b = 0.7665, and c = 0.4681 with

$$R_{e_d} = \frac{\rho_e U_e d}{12 \mu_e} \tag{19}$$

and

$$F_1 = \left(\frac{\nu_e}{\nu^*}\right)\left(\frac{M_p}{M_e}\right) R_{e_d} \sqrt{\frac{1 + \frac{\gamma-1}{2} M_e^2}{1 + \frac{\gamma-1}{2} M_p^2}} \tag{20}$$

Since Equations 16, 17, and 18 resulted in skin friction coefficients very nearly the same, the R.M.S. value

$$(C_f)_p = \sqrt{\frac{1}{3}\left[(C_f)_Y^2 + (C_f)_{HK}^2 + (C_f)_A^2\right]} \tag{21}$$

was used. A few representative values have been calculated using Equations 16, 17, 18 and 21 and are tabulated in Table 2. The corresponding Van Driest (Reference 11 and 14) skin friction coefficient and the percent difference between Equation 21 and the Van Driest theory [14] are also included. Based on these results, it would appear that the use of Equation 21 is justified.

The Von Karman integral method was the third method used to calculate the skin friction coefficient. It was introduced primarily as a check on the values measured with the balance and the Preston tube. Since the Von Karman integral method makes use of the boundary layer history, it becomes necessary to find an expression for each term in the Von Karman integral equation (see Equation 22) as a function of the longitudinal distance "x".

$$(C_f)_{VK} = 2\left[\frac{d\theta}{dx} + \left(2 + \frac{\delta^*}{\theta} - M_e^{\,2}\right)\left(\frac{\frac{\theta}{M_e}\,\frac{dM_e}{dx}}{1 + \frac{\gamma-1}{2}M_e^{\,2}}\right)\right] \tag{22}$$

The empirical equations formulated by Fiore[7] were used in this calculation, these expressions are only valid for zero pressure gradient at near adiabatic wall conditions and for a nominal Mach number of three, they are:

$$\frac{d\theta}{dx} = 4.28442 \times 10^{-4}\,\frac{M_e^{\,1.1109}}{R_{e_x}^{\,0.0507}}\left[1-2.0596 \times 10^{-3}\left(\frac{x}{M_e}\right)\right] \tag{23}$$

$$\frac{\delta^*}{\theta} = 7.1496\,\frac{M_e^{\,0.7992}}{R_{e_x}^{\,0.0518}} \tag{24}$$

and

$$M_e = -0.00176X + 3.0282 \tag{25}$$

The skin friction coefficients calculated using Equations 10, 21, and 22 are presented in both tabular and graphical form in this report.

The skin friction coefficients obtained by all three methods are compared with one another as well as with various theories and are analyzed in the next section. The detailed equations for the theories of Van Driest (References 11 and 14) and Wilson[10] along with the semi-empirical method of Spalding-Chi (References 15 and 16) are presented in Appendix A of this report. Shang's code is not presented because of its complexity, however it is described in Reference 12.

# SECTION V

# TEST RESULTS

## 1. BALANCE MEASUREMENTS

The skin friction coefficients obtained by direct measurements with a balance are presented as a plot of $C_f$ versus $R_{e_\theta}$ in Figure 5 and $C_f$ versus $R_{e_x}$ in Figure 6. In both cases they are compared with the measurements of Matting et al.[9], and those of Moore and Harkness[1]. They are also compared with the theories of Wilson[10], Van Driest[14], Spalding-Chi[15], and the calculations of Shang et al.[12]. The measurements agree with Matting's data in the range of momentum thickness Reynolds numbers extending from $2 \times 10^4$ to $5 \times 10^4$. As $R_{e_\theta}$ increases from $5 \times 10^4$ to approximately $25 \times 10^4$ the new measurements scatter about the two points of Moore and Harkness by approximately ±10%. For momentum thickness Reynolds numbers greater than $25 \times 10^4$, the measurements appear to be equal to and slightly greater than the data of Moore and Harkness.

When the measurements are compared with the previously mentioned theories, the agreement between them is good. As shown in Figure 5, the skin friction measurements throughout the Reynolds number range of this investigation agree within ±15% of the Wilson, Van Driest, and the Spalding-Chi theories as well as Shang's code.

From Figure 5 we note that in the range $2 \times 10^4 \leq R_{e_\theta} \leq 35 \times 10^4$ the present skin friction measurements and those of Moore and Harkness are in agreement with each other; however, both are slightly greater than the theories shown. For $R_{e_\theta} \geq 35 \times 10^4$, all the theories tend to underestimate the measured skin friction coefficients by approximately 8 to 15%, depending upon the particular theory used. (See Figure 7 through 10.)

A least square fit to the measurements shown in Figures 5 and 6 resulted in the following empirical expression for the skin friction coefficient

$$C_f = \frac{4.435 \times 10^{-3}}{R_{e_\theta}^{\ 0.1244}} \tag{26}$$

and

$$C_f = \frac{11.566 \times 10^{-3}}{M_e^{\ 0.139} \ R_{e_x}^{\ 0.118}} \tag{27}$$

Equation 26 is valid in the range of Reynolds numbers $2 \times 10^4 \leq R_{e_\theta} \leq 50 \times 10^4$ while Equation 27 is valid in the corresponding range of $2 \times 10^7 \leq R_{e_x} \leq 1.5 \times 10^9$. Both Equations 26 and 27 are restricted to a near adiabatic wall with zero pressure gradient, and a nominal Mach number of three.

## 2. PRESTON TUBE MEASUREMENTS

The skin friction coefficient, obtained with a Preston tube, are presented in Figures 11 and 12 as a function of the momentum thickness and length Reynolds number respectively. In both these figures, the Preston tube data are compared with the experimental measurements of Matting et al.[9], and Moore-Harkness[1]. They are also compared with the theories of Wilson[10], Spalding-Chi[15], Van Driest[14] and Shang et al.[12]. Figures 11 and 12 indicate that the skin friction coefficients obtained in this manner are slightly below both the Matting and the Moore-Harkness results. In the Reynolds number range extending from $R_{e_\theta} = 2 \times 10^4$ to approximately $R_{e_\theta} = 30 \times 10^4$ all the theories shown in Figure 11 overpredict the measured skin friction coefficients; however, they agree very well with all the theories in the higher Reynolds number range of $30 \times 10^4 \leq R_{e_\theta} \leq 50 \times 10^4$.

The percent difference between the Preston tube skin friction measurements and those calculated from the theories of Van Driest, Spalding-Chi, Wilson and Shang are shown in Figures 13 through 16 respectively. The variation in the measured skin friction coefficient with respect to the Van Driest theory is shown in Figure 13. The maximum difference occurs at $R_{e_\theta} = 3 \times 10^4$, where the skin friction coefficient varies from 4% higher to 20% lower than the Van Driest theory. As the momentum Reynolds number is increased, the percent difference between the Preston tube measurements and the Van Driest theory decreases significantly. In the Reynolds number range given as $30 \times 10^4 \leq R_{e_\theta} \leq 50 \times 10^4$ the measured skin friction coefficient is about four percent lower than the Van Driest theory.

Figure 14 shows the variation between the Preston tube skin friction coefficient and that calculated from the Spalding-Chi theory as a function of the momentum thickness Reynolds number. The percent variation between the measurements and theory as a function of $R_{e_\theta}$ is similar to that shown in Figure 13, i.e., the percent difference is highest at the lower Reynolds numbers and decreases with increasing Reynolds number. The Spalding-Chi theory overpredicts the measurements by about an average of 8% at $R_{e_\theta} = 4 \times 10^4$; however, as the momentum thickness Reynolds number is increased to $50 \times 10^4$, the Spalding-Chi theory overpredicts the measurements by approximately two percent.

The percent difference between the Preston tube skin friction coefficient and those calculated from Wilson's theory are presented in Figure 15. Wilson's theory overpredicts the measurements by an average of approximately 8%. The scatter in the data changes significantly over the total range of Reynolds numbers. As seen in Figure 15 the maximum scatter occurs in the range $2 \times 10^4 \leq R_{e_\theta} \leq 25 \times 10^4$ and it decreases as the Reynolds number is increased.

The minimum scatter occurs in the Reynolds number range given as $25 \times 10^4 \leq R_{e_\theta} \leq 50 \times 10^4$.

The corresponding difference between $(C_f)_p$ and those calculated by Shang are shown in Figure 16. At a Reynolds number of $3 \times 10^4$ the scatter is such that $(C_f)_p$ varies from 4% greater to 14% smaller than Shang's theory. As the Reynolds number is increased this difference remains nearly constant; and the skin friction measurements are about two percent lower than the theory in the Reynolds number range $25 \times 10^4 \leq R_{e_\theta} \leq 50 \times 10^4$.

3. VON KARMAN INTEGRAL RESULTS

The skin friction coefficients obtained from the Von Karman integral method are plotted versus the momentum thickness and length Reynolds number in Figures 17 and 18 respectively. The skin friction coefficients in the momentum Reynolds number range extending from $R_{e_\theta} = 2 \times 10^4$ to $R_{e_\theta} = 10^5$ fall well below the measurements of Matting as well as the four theories shown in Figure 17. This is reflected in Figures 19 through 22 where the percent difference between the Von Karman skin friction coefficient and the various theories are presented. In each case the Von Karman integral method yields skin friction values which are considerably less than the various theories. For example, the Von Karman skin friction coefficients are from 2% to 18% less than those predicted by the four theories shown in Figures 19 through 22.

As the momentum thickness Reynolds number is increased from $10^5$ to $50 \times 10^4$, the Von Karman integral method yields a near constant value of $(C_f)_{VK}$. Although the agreement between $(C_f)_{VK}$, the experimental measurements, and the four theories are reasonably good, it is not completely correct since the skin friction coefficient should continuously decrease with increasing $R_{e_\theta}$ rather than remain constant. The cause is due to the fact that each term in Equation 22 is not known with the desired degree of accuracy in order to insure a monotonic decrease in $(C_f)_{VK}$ with increasing $R_{e_\theta}$. It should be noted, however, that an increase in the momentum thickness Reynolds number beyond $10^5$ produces values of $(C_f)_{VK}$ which are larger than the previously mentioned four theories by about four to six percent.

# SECTION VI

# CONCLUSIONS

An investigation was conducted at a nominal Mach number of three over the momentum thickness Reynolds number extending from $2 \times 10^4$ to approximately $50 \times 10^4$. The purpose of this study was to make skin friction measurements at very high Reynolds numbers for near adiabatic wall conditions and zero pressure gradient. The skin friction coefficients were obtained by three methods: they were measured directly with a balance, with a Preston tube, and they were calculated using the Von Karman integral method. The results of this investigation are summarized as follows:

(1) The skin friction coefficient obtained with a balance and the Preston tube agree with the measurements of Matting et al. within 7%, and are within 4% of the Moore and Harkness measurements.

(2) The theories of Van Driest, Spalding-Chi, Wilson, and Shang appear to be reasonably good in the range $2 \times 10^4 \leq R_{e_\theta} \leq 30 \times 10^4$. Above $R_{e_\theta} = 30 \times 10^4$, all four theories underpredict by approximately ten percent the measured skin friction coefficients obtained in this investigation, as well as those measured by Moore and Harkness.

(3) The Von Karman integral method with Fiore's empirical relations(7) yields skin friction coefficients which are too low compared to the measurements of Matting in the Reynolds number range $2 \times 10^4 \leq R_{e_\theta} \leq 10^5$. They are also too low with references to the theories of Van Driest, Spalding-Chi, Wilson, and Shang. For Reynolds number extending from $R_{e_\theta} = 10 \times 10^4$ to approximately $50 \times 10^4$, the Von Karman integral method results in a near constant skin friction coefficient which violates the concept of decreasing skin friction as the Reynolds number tends to infinitely larger values. The method can be improved, provided each term in the Von Karman integral equation can be expressed more accurately.

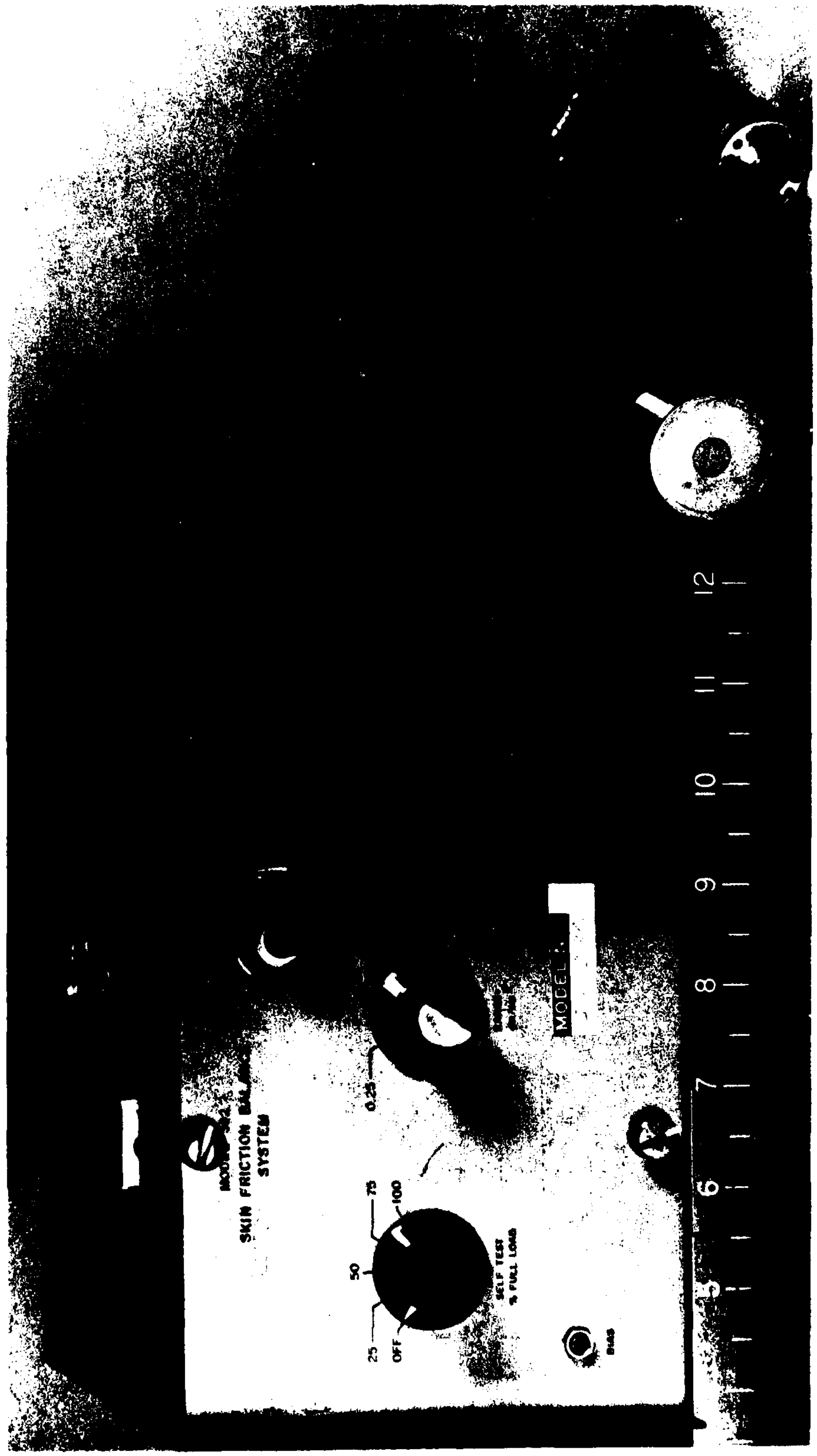


Figure 1. Floating-Element Skin Friction Balance

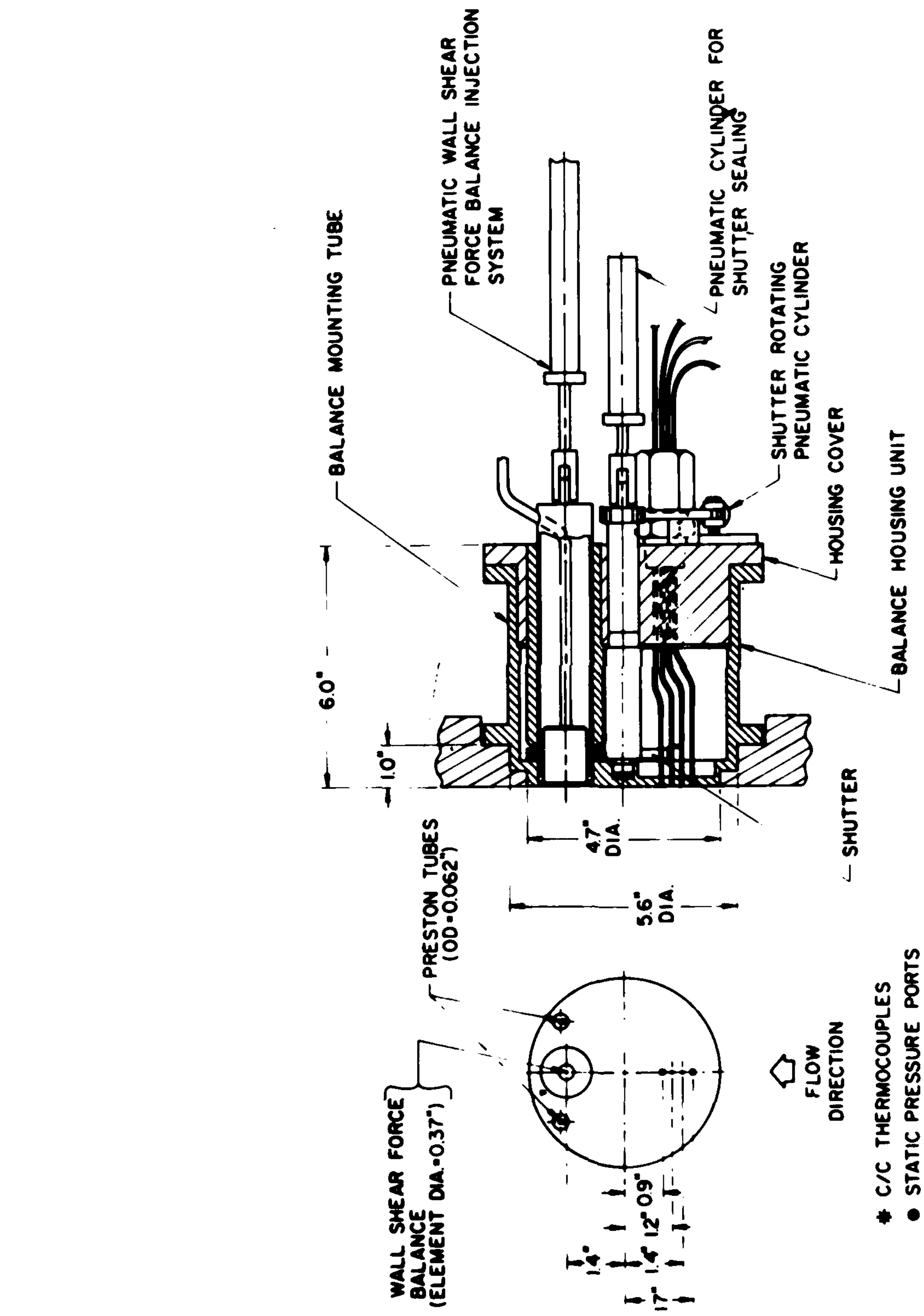


Figure 2. Drawing of Wall Shear Force Balance Injection System and Related Instrumentation

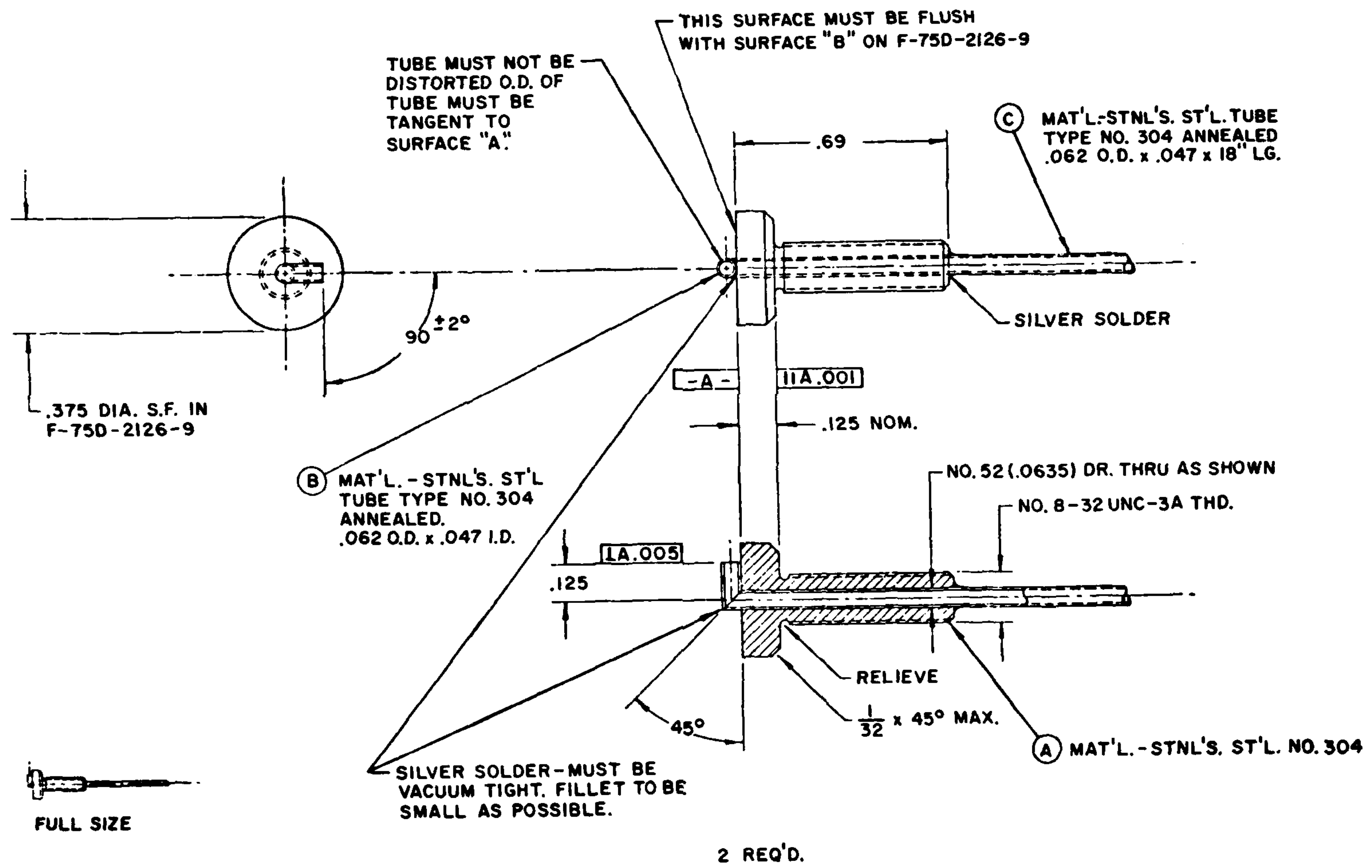


Figure 3. Detailed Design of the Preston Tubes

| STATION NUMBER | DISTANCE FROM NOZZLE THROAT (INCHES) | STATION NUMBER | DISTANCE FROM NOZZLE THROAT (INCHES) |
|---|---|---|---|
| 1 | 27.28 | 5 | 82.28 |
| 2 | 43.28 | 6 | 94.28 |
| 3 | 58.28 | 7 | 106.28 |
| 4 | 70.28 | 8 | 118.28 |

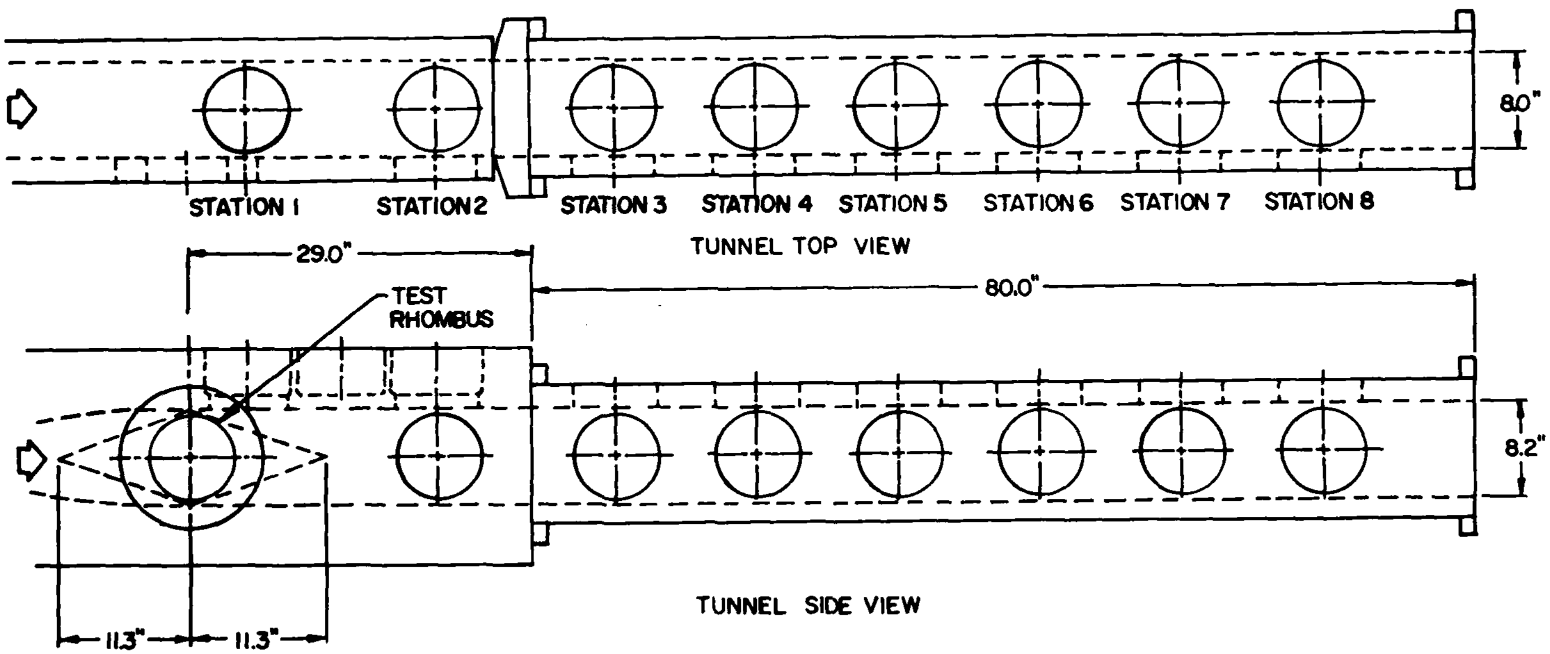


Figure 4. Tunnel Test Section and Diffuser Section Schematic

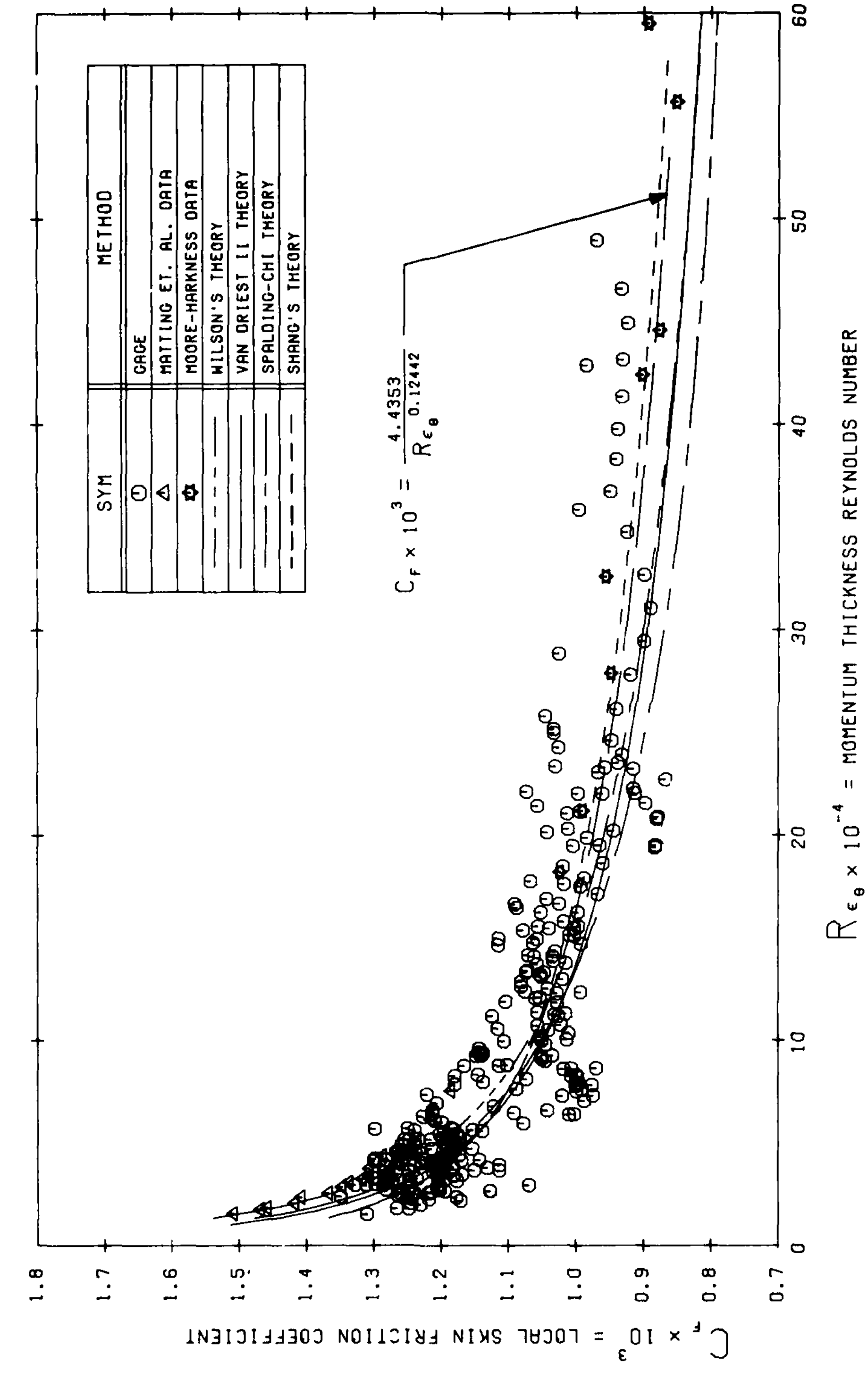


Figure 5. Local Skin Friction Coefficient Versus Momentum Thickness Reynolds Numbers for Near Adiabatic Wall Temperature and $M_e$ = 2.88

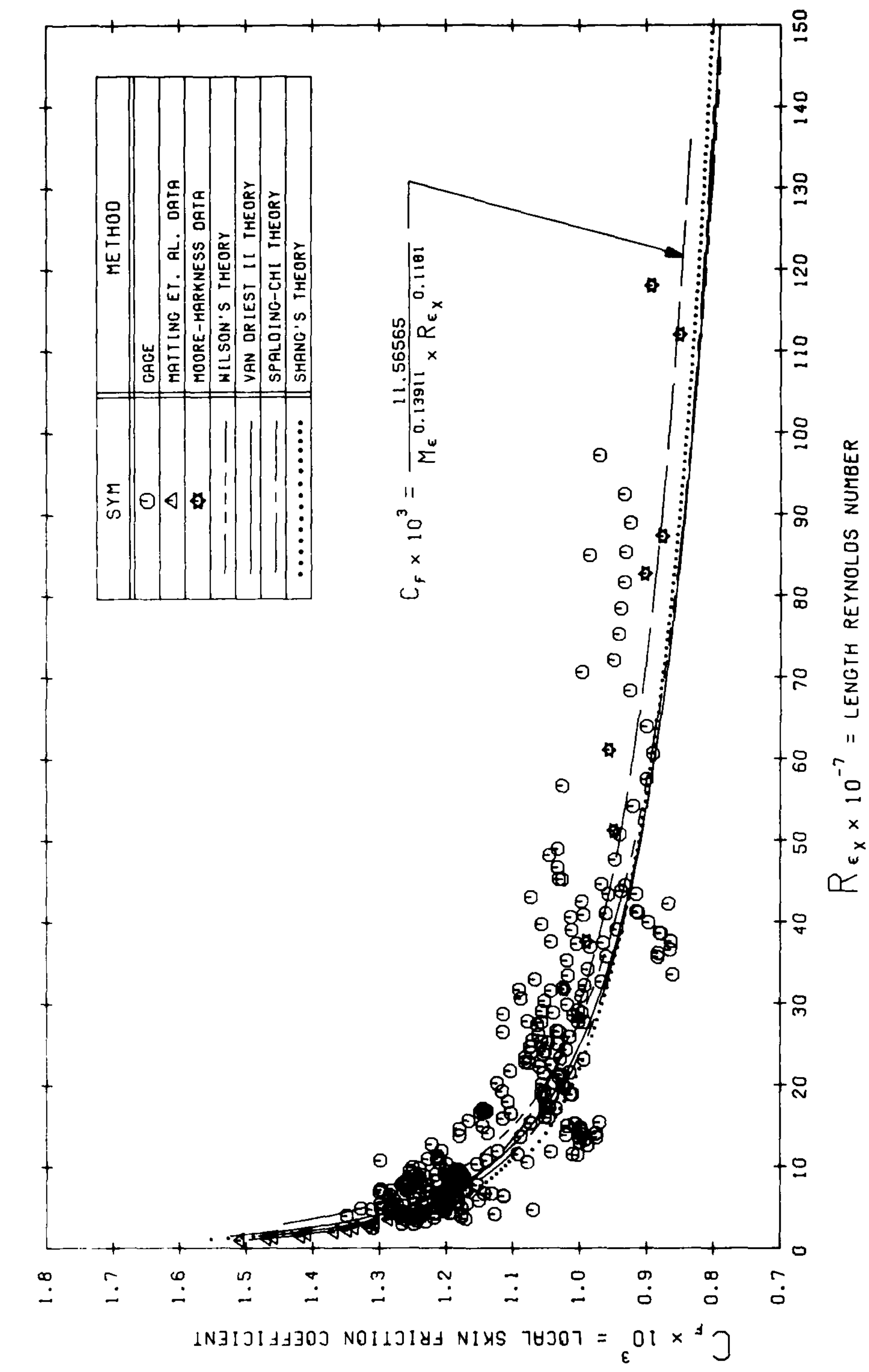


Figure 6. Local Skin Friction Coefficient Versus the Length Reynolds Number for Near Adiabatic Wall Temperature and $M_e = 2.88$

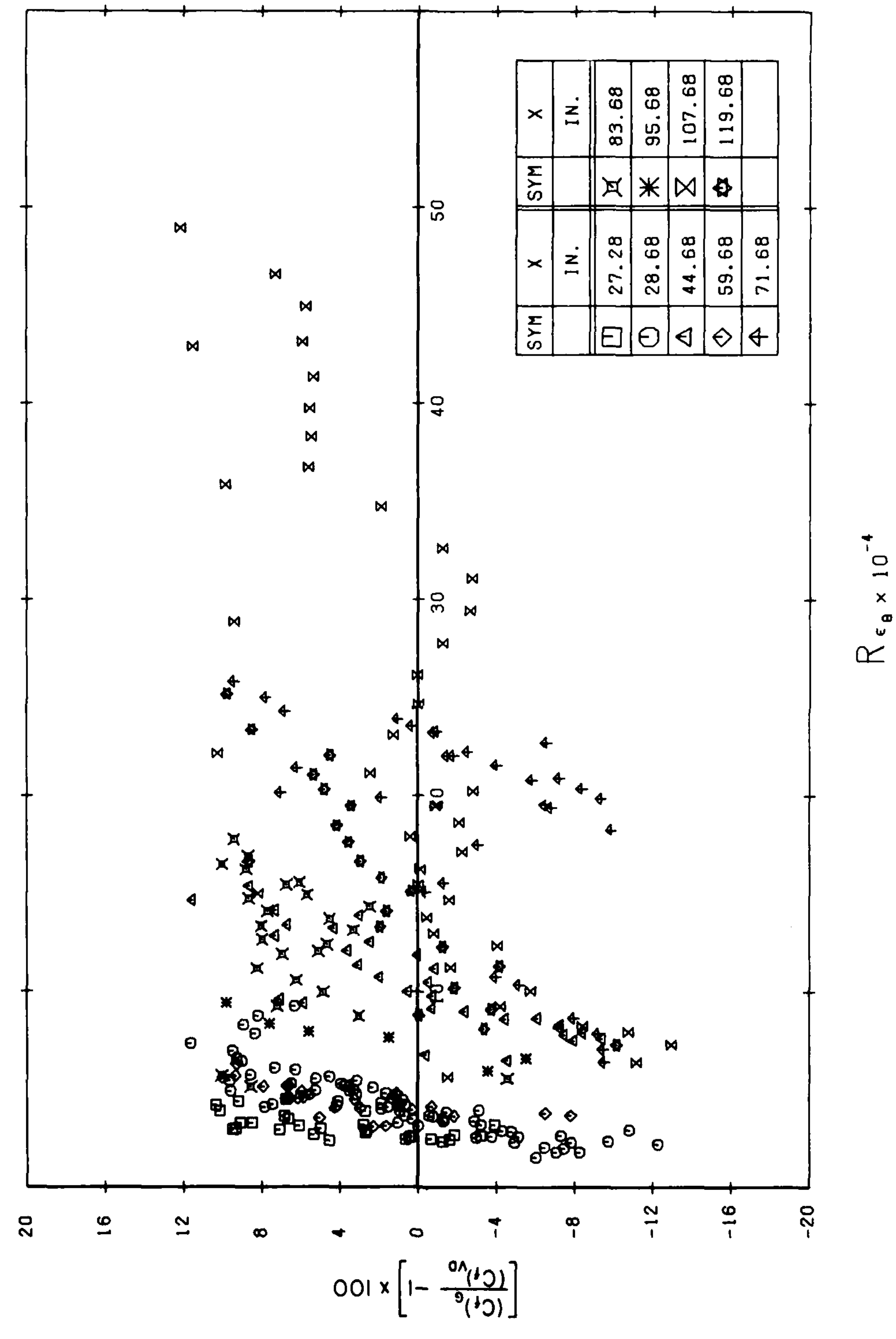


Figure 7. Percent Difference Between Gage Measurements and Van Driest Theory Versus Momentum Reynolds Number for Near Adiabatic Wall Temperature and $M_e = 2.88$

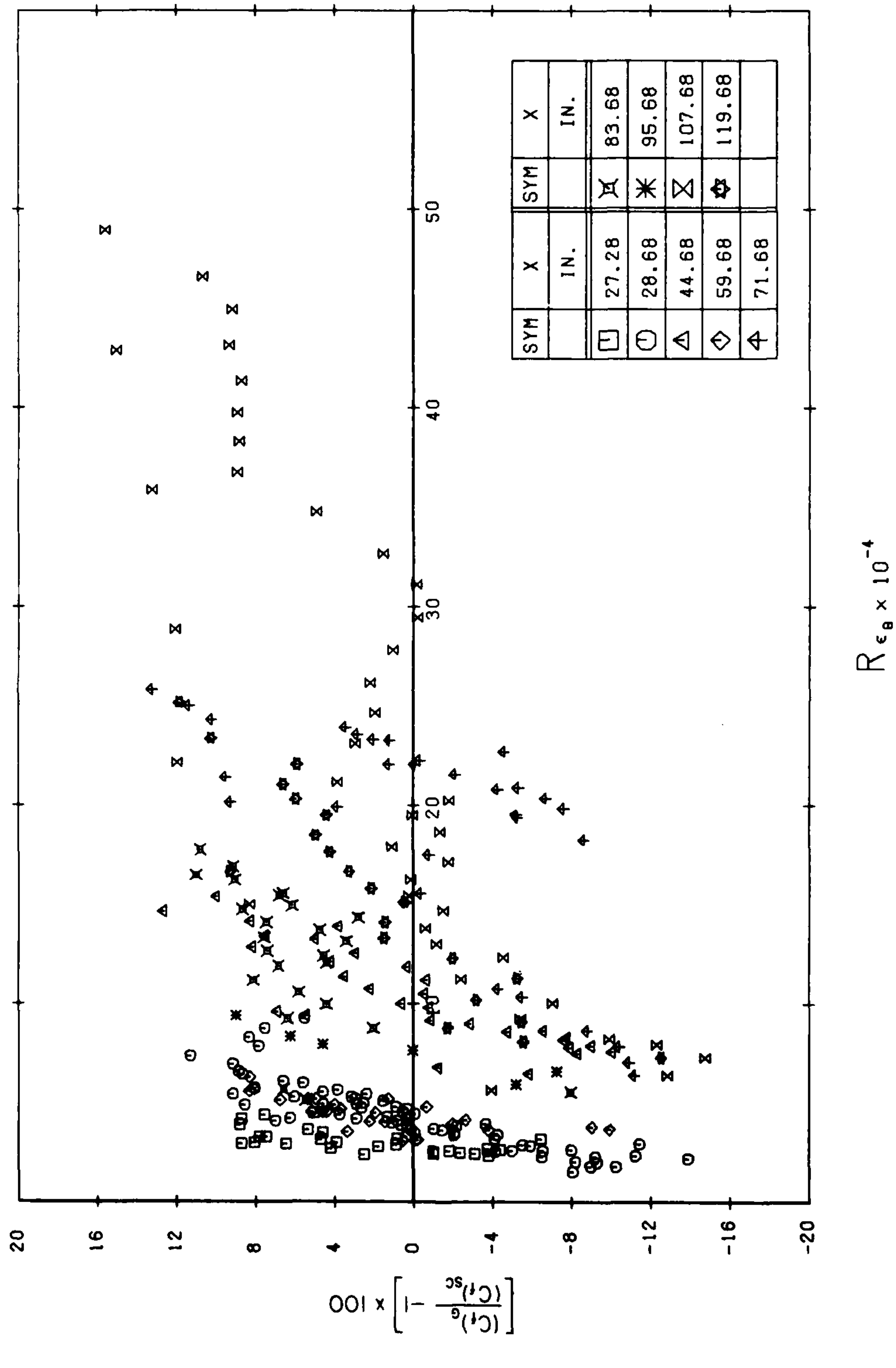


Figure 8. Percent Difference Between Gage Measurements and Spalding-Chi Theory Versus Momentum Reynolds Number for Near Adiabatic Wall Temperature and $M_e = 2.88$

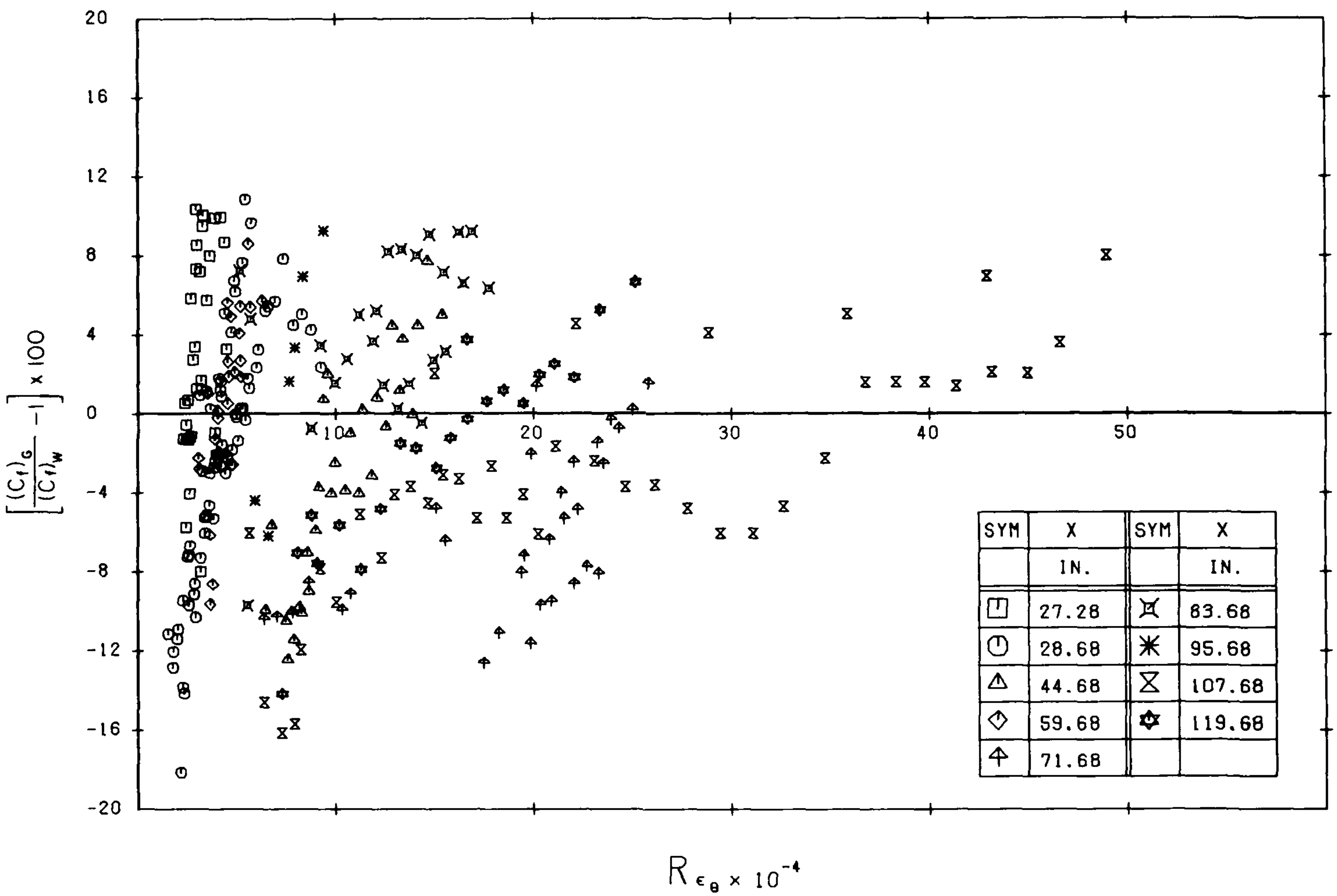


Figure 9. Percent Difference Between Gage Measurements and Wilson Theory Versus Momentum Reynolds Number for Near Adiabatic Wall Temperature and $M_e$ = 2.88

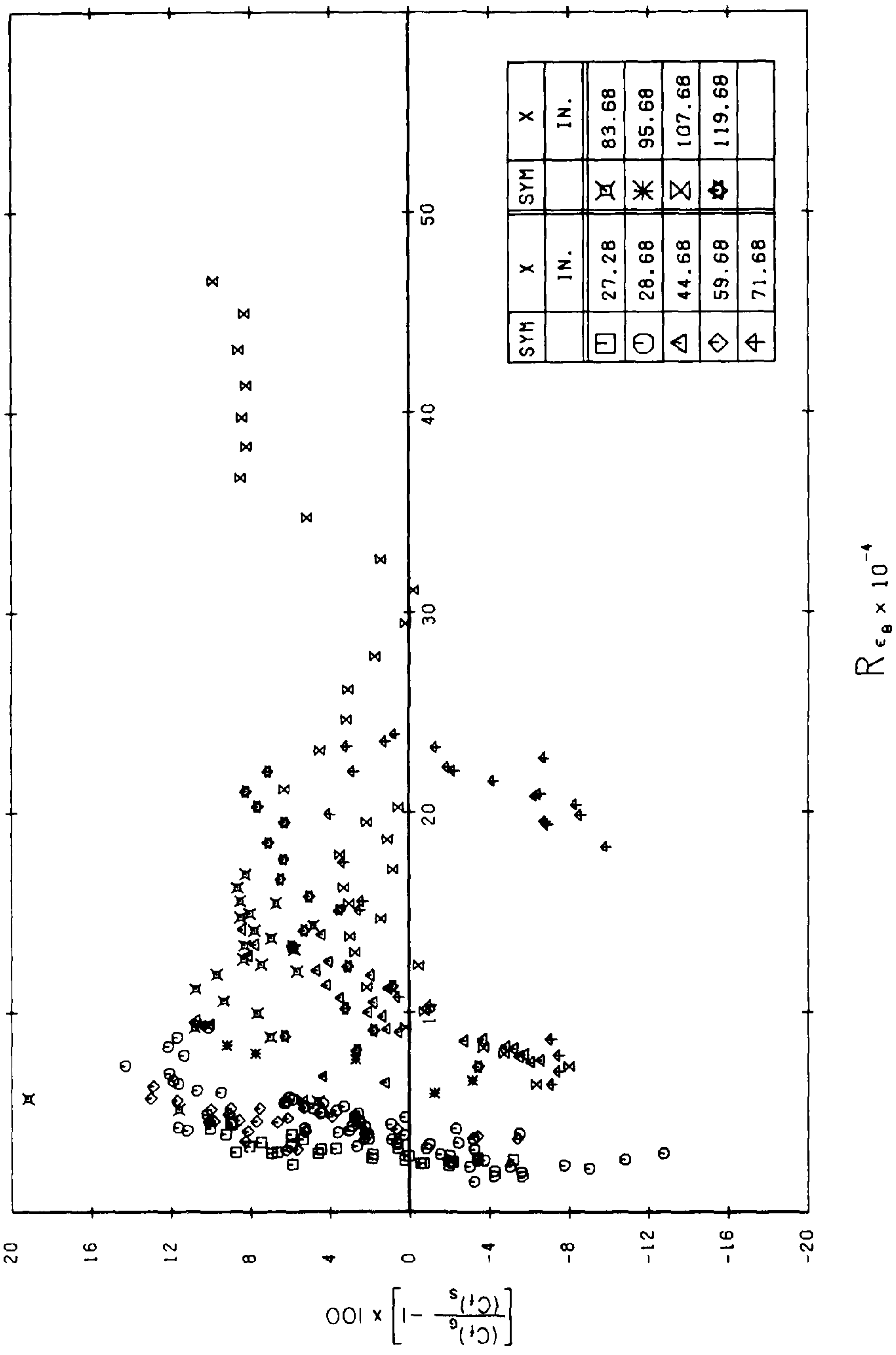


Figure 10. Percent Difference Between Gage Measurements and Shang Theory Versus Momentum Reynolds Number for Near Adiabatic Wall Temperature and $M_e$ = 2.88

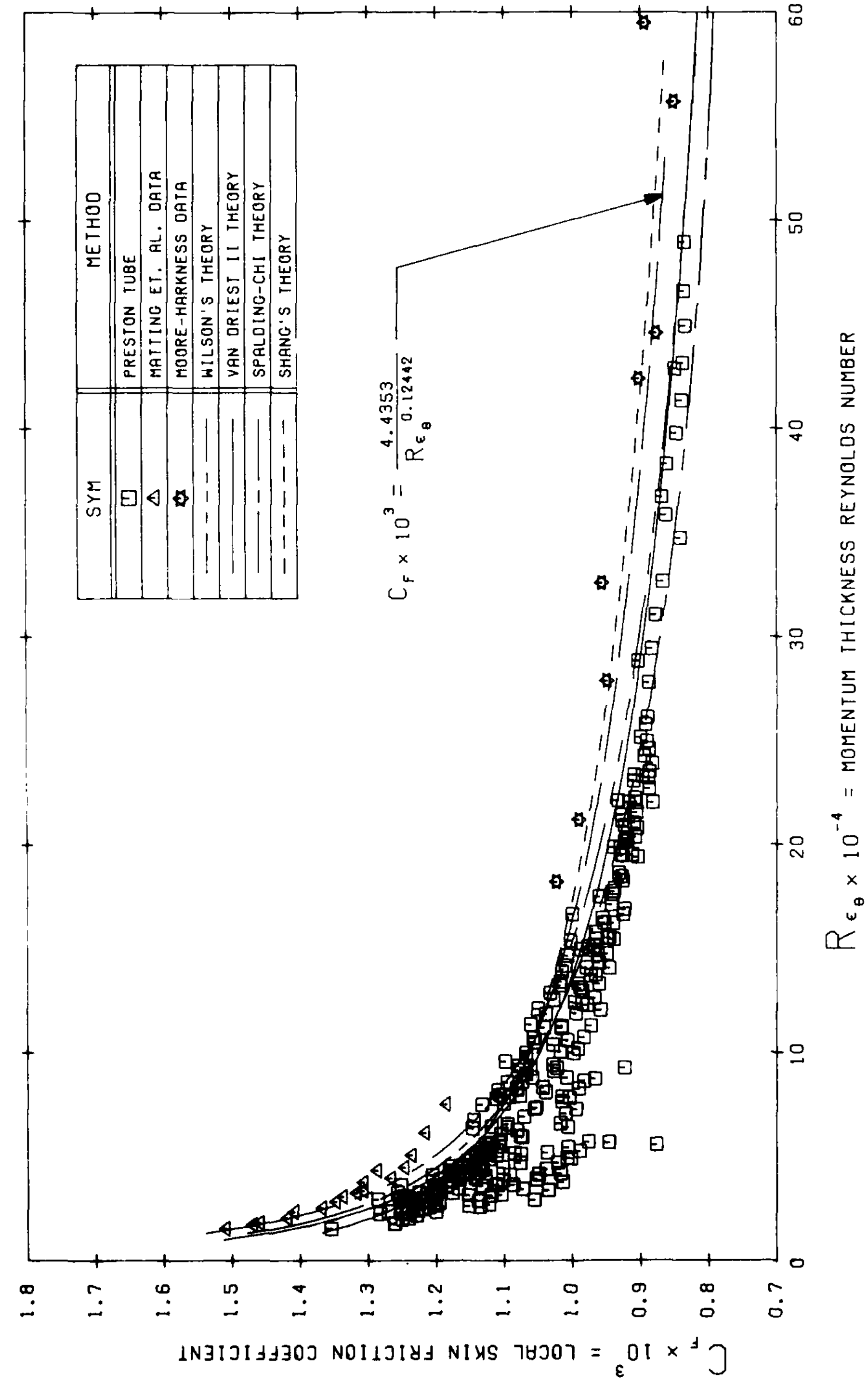


Figure 11. Local Skin Friction Versus Momentum Thickness Reynolds Number for Near Adiabatic Wall Temperature and $M_e$ = 2.88

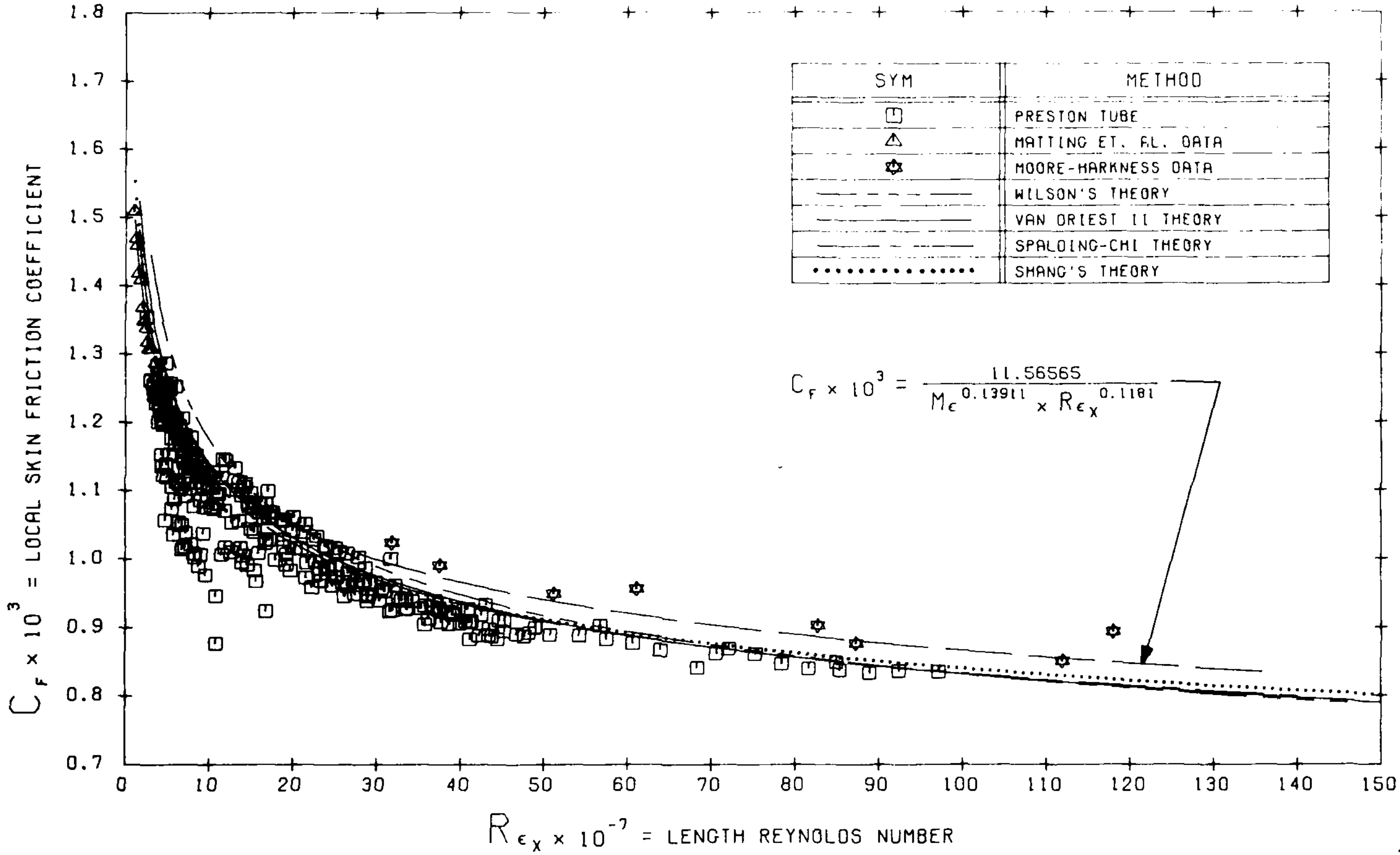


Figure 12. Local Skin Friction Coefficient Versus the Length Reynolds Number for Near Adiabatic Wall Temperature and $M_e$ = 2.88

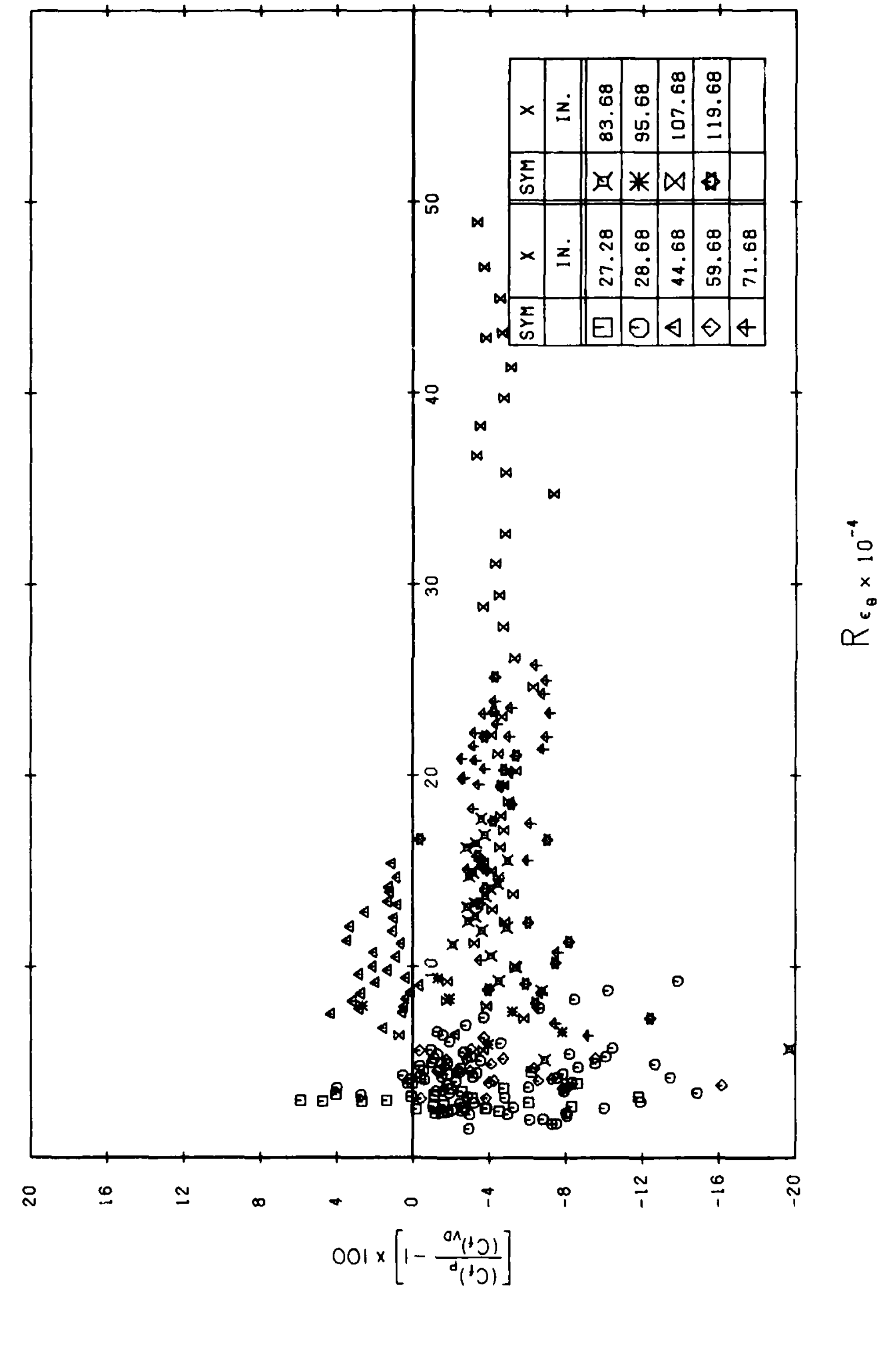


Figure 13. Percent Difference Between Preston Tube Measurements and Van Driest Theory Versus Momentum Reynolds Number for Near Adiabatic Wall Temperature and $M_e$ = 2.88

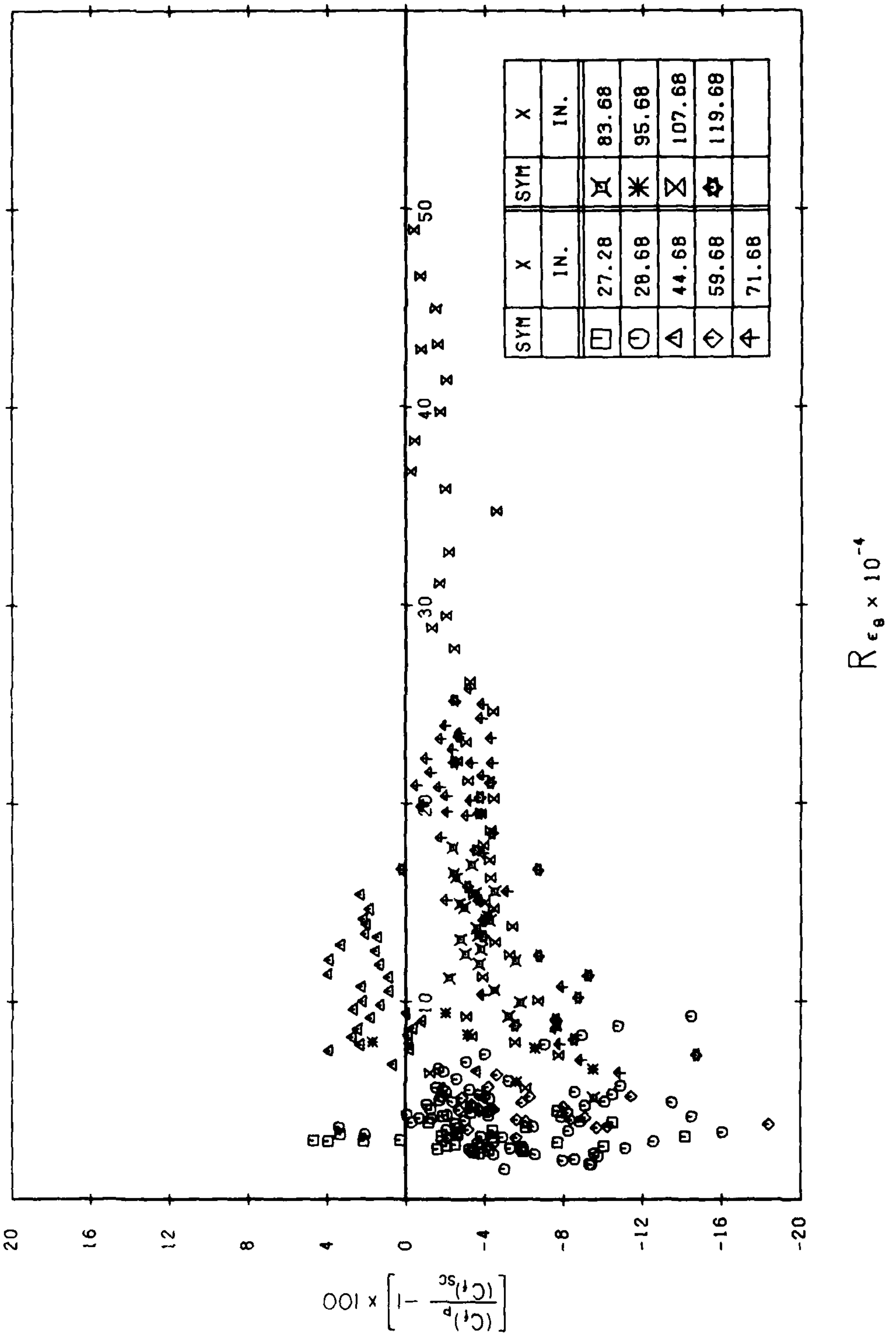


Figure 14. Percent Difference Between Preston Tube Measurements and Spalding-Chi Theory Versus Momentum Reynolds Number for Near Adiabatic Wall Temperature and $M_e$ = 2.88

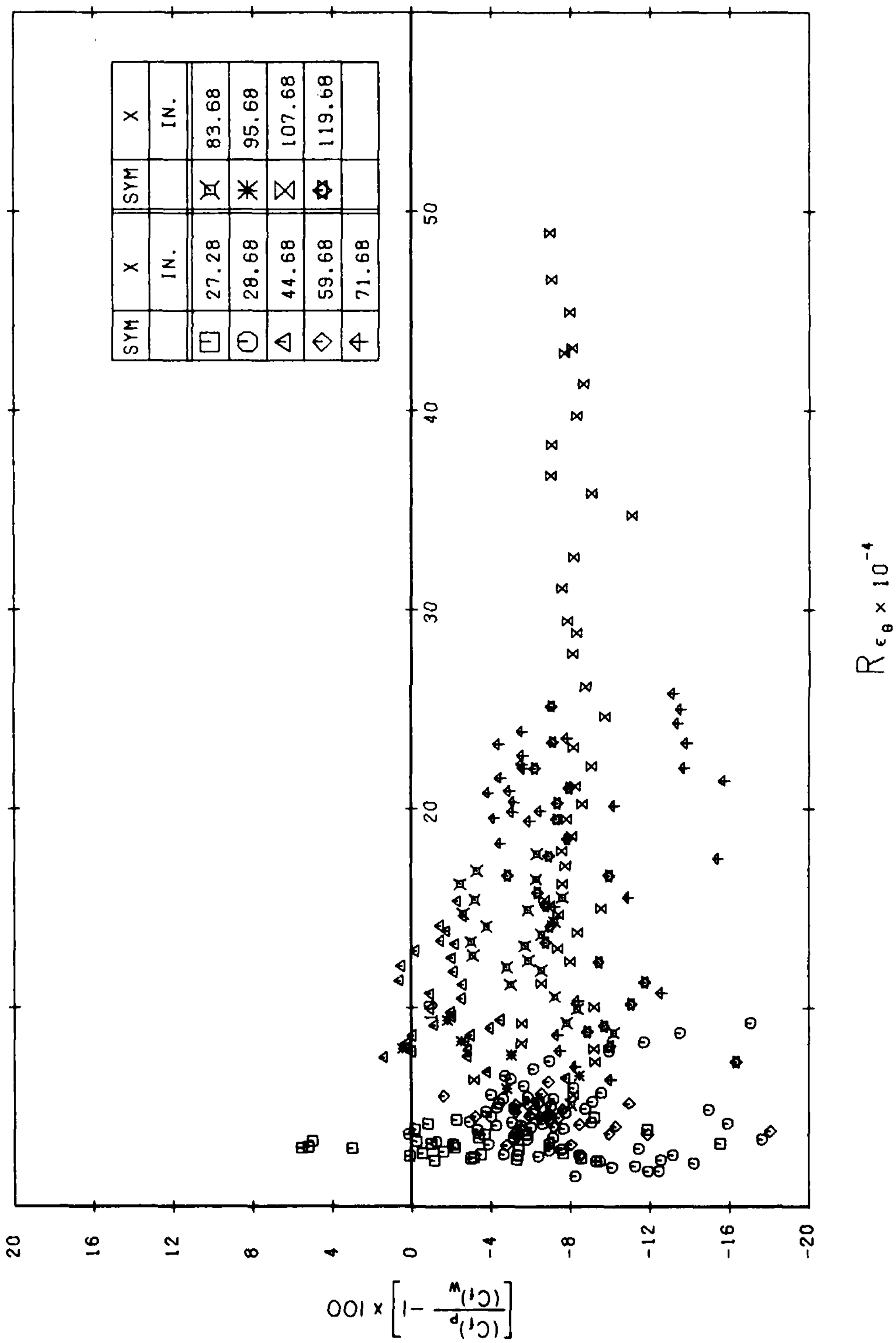


Figure 15. Percent Difference Between Preston Tube Measurements and Wilson Theory Versus Momentum Reynolds Number for Near Adiabatic Wall Temperature and $M_e = 2.88$

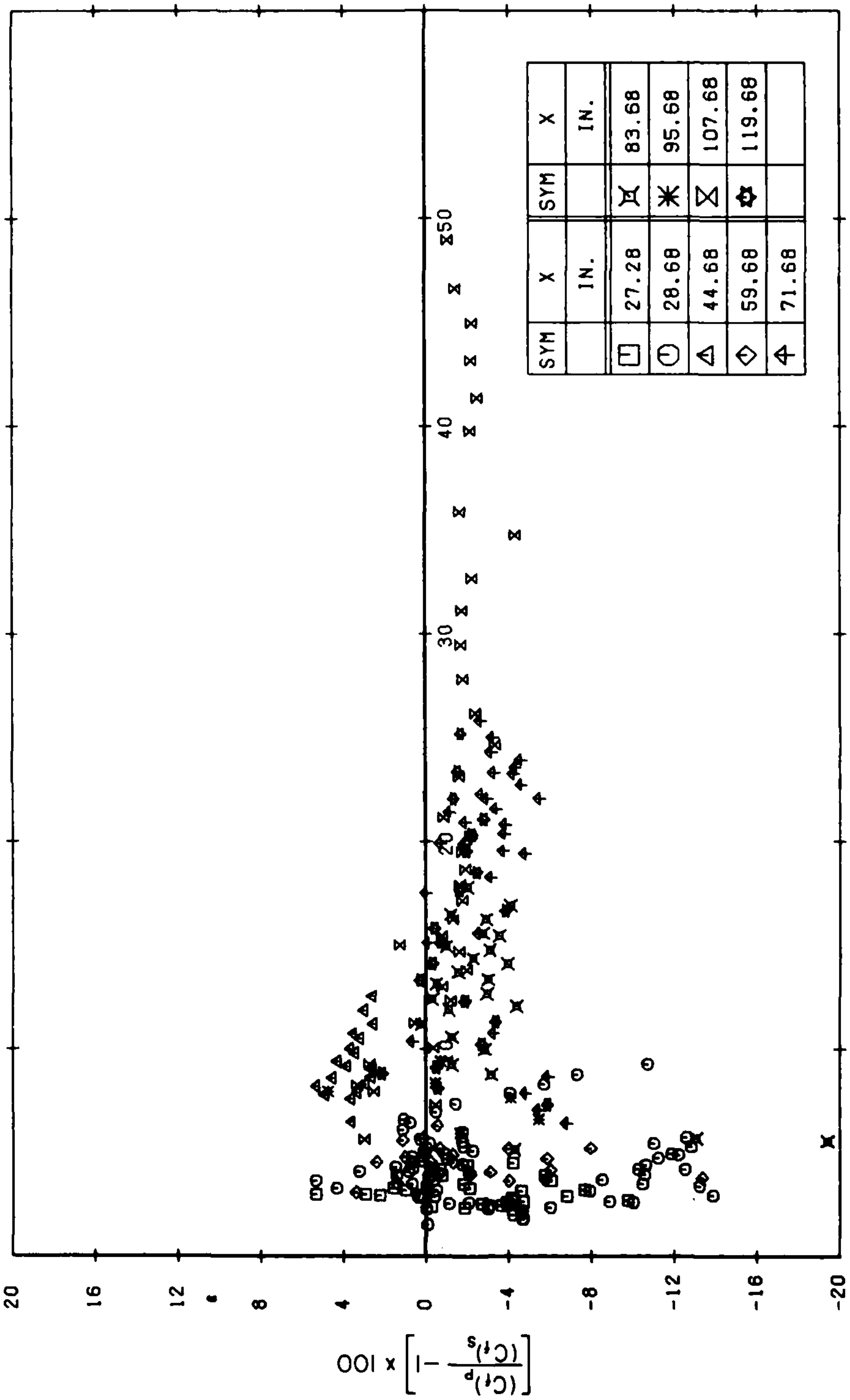


Figure 16. Percent Difference Between Preston Tube Measurements and Shang Theory Versus Momentum Reynolds Number for Near Adiabatic Wall Temperature and $M_e = 2.88$

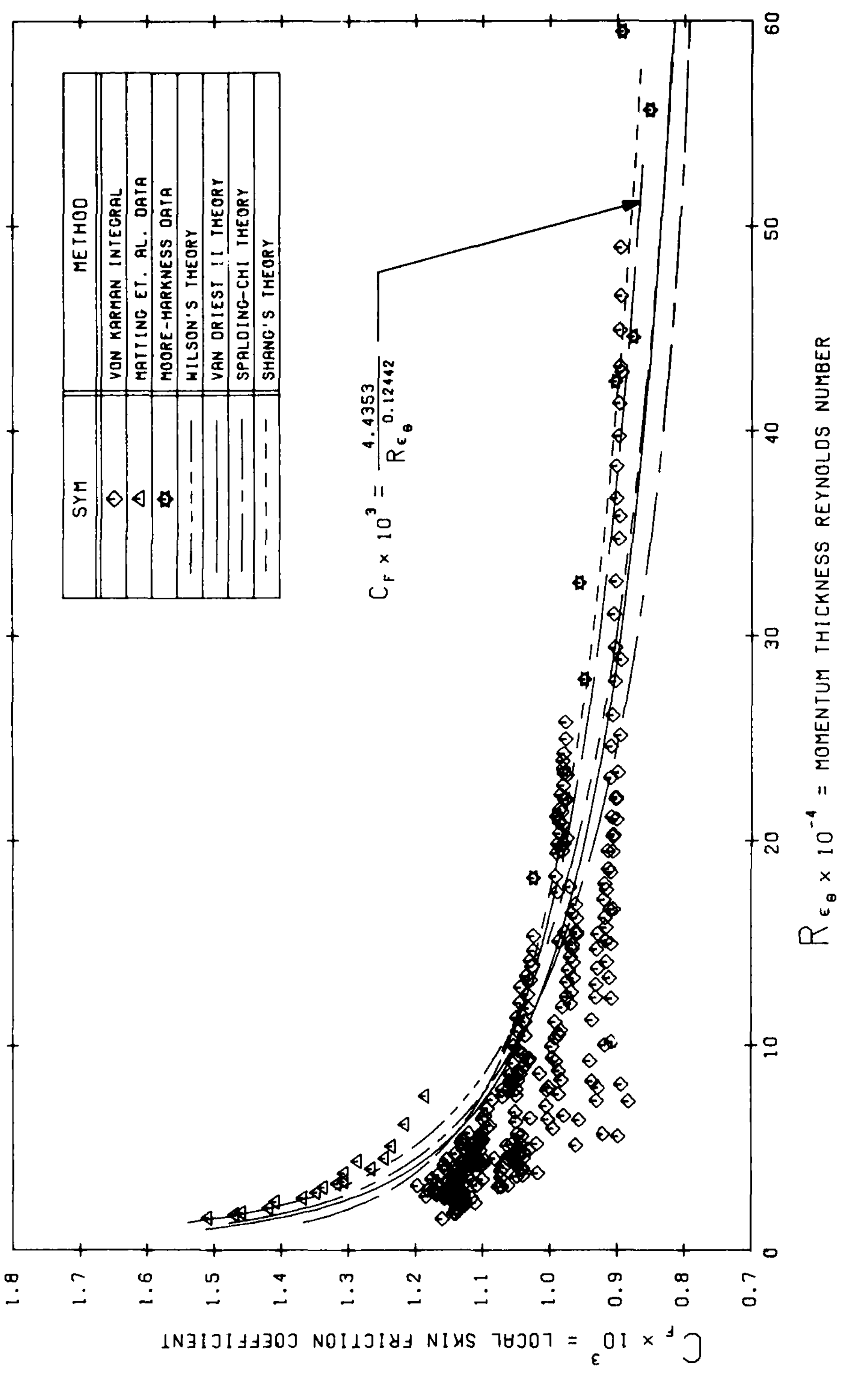


Figure 17. Local Skin Friction Coefficient Versus Momentum Thickness Reynolds Number for Near Adiabatic Wall Temperature and $M_e = 2.88$

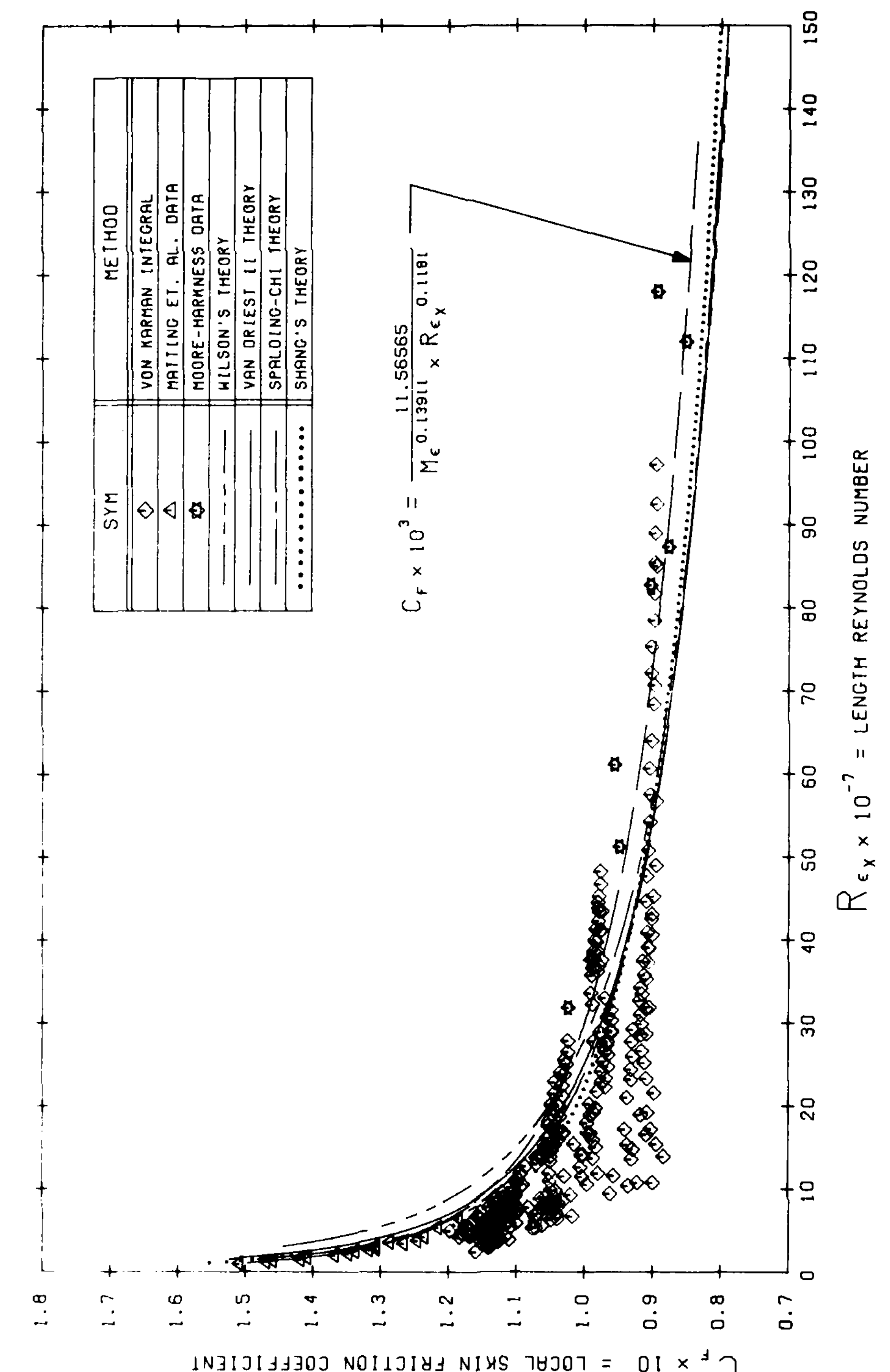


Figure 18. Local Skin Friction Coefficient Versus the Length Reynolds Number for Near Adiabatic Wall Temperature and $M_e = 2.88$

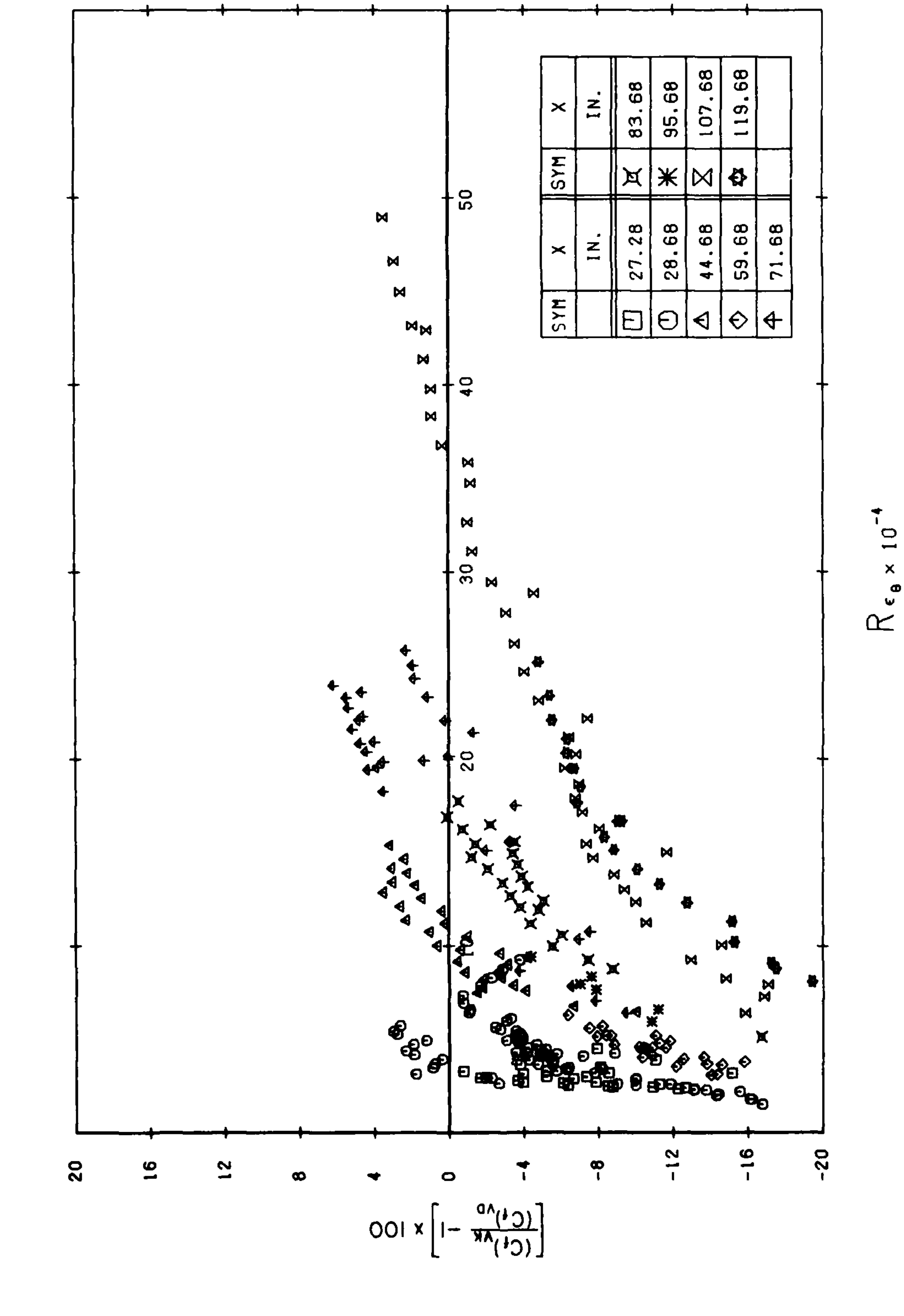


Figure 19. Percent Difference Between Von Karman Measurements and Van Driest Theory Versus Momentum Reynolds Number for Near Adiabatic Wall Temperature and $M_e$ = 2.88

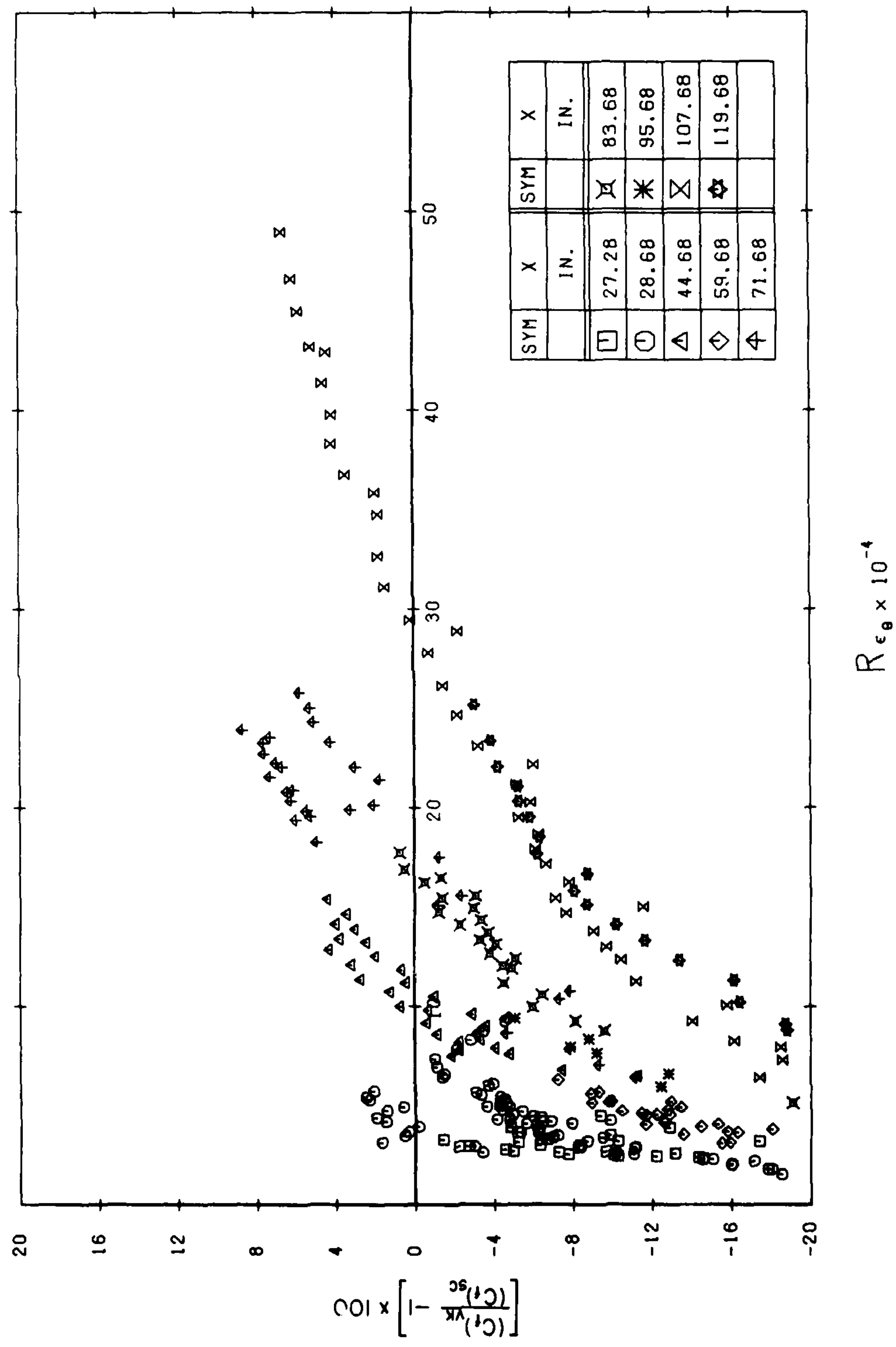


Figure 20. Percent Difference Between Von Karman Measurements and Spalding-Chi Theory Versus Momentum Reynolds Number for Near Adiabatic Wall Temperature and $M_e$ = 2.88

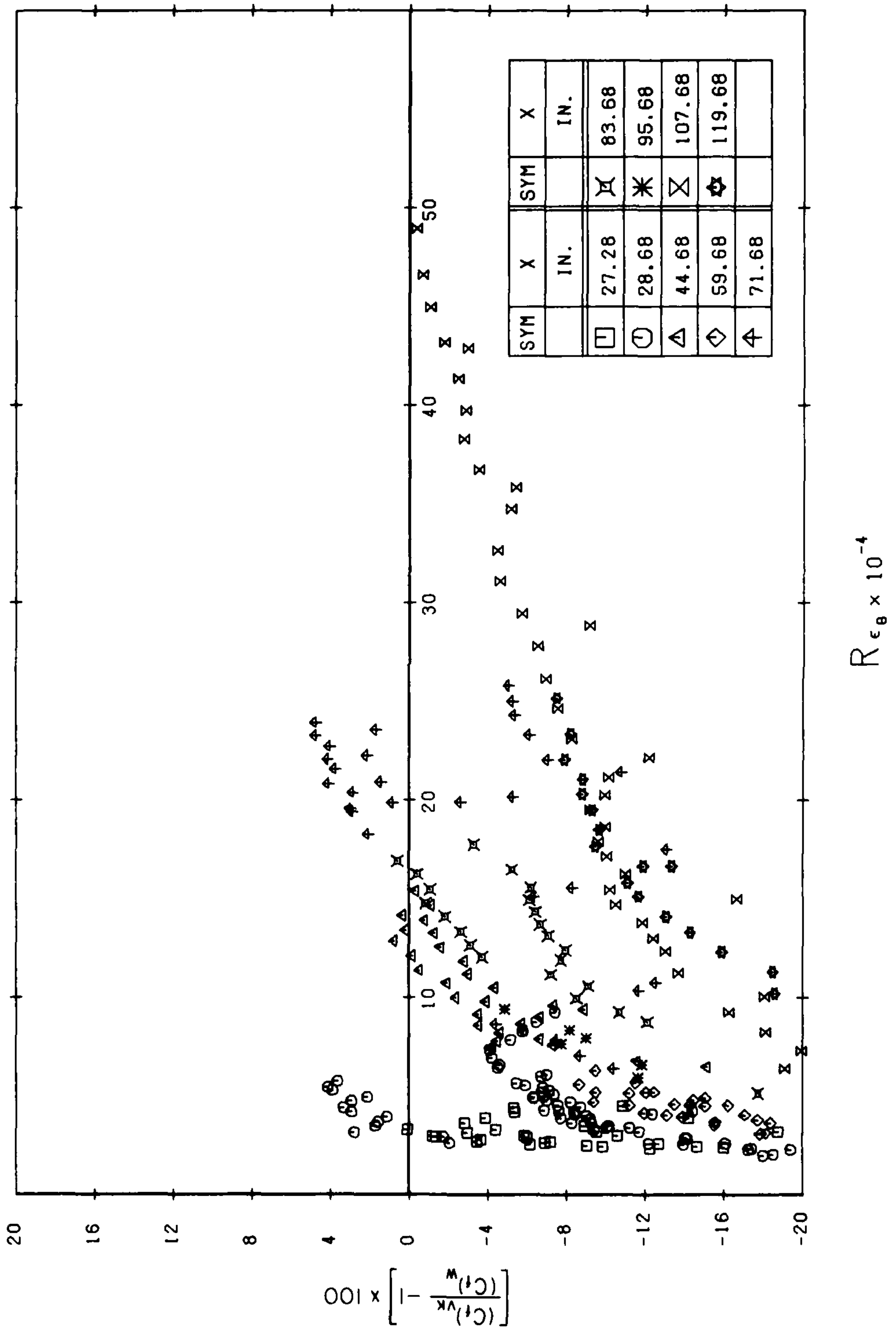


Figure 21. Percent Difference Between Von Karman Measurements and Wilson Theory Versus Momentum Reynolds Number for Near Adiabatic Wall Temperature and $M_e = 2.88$

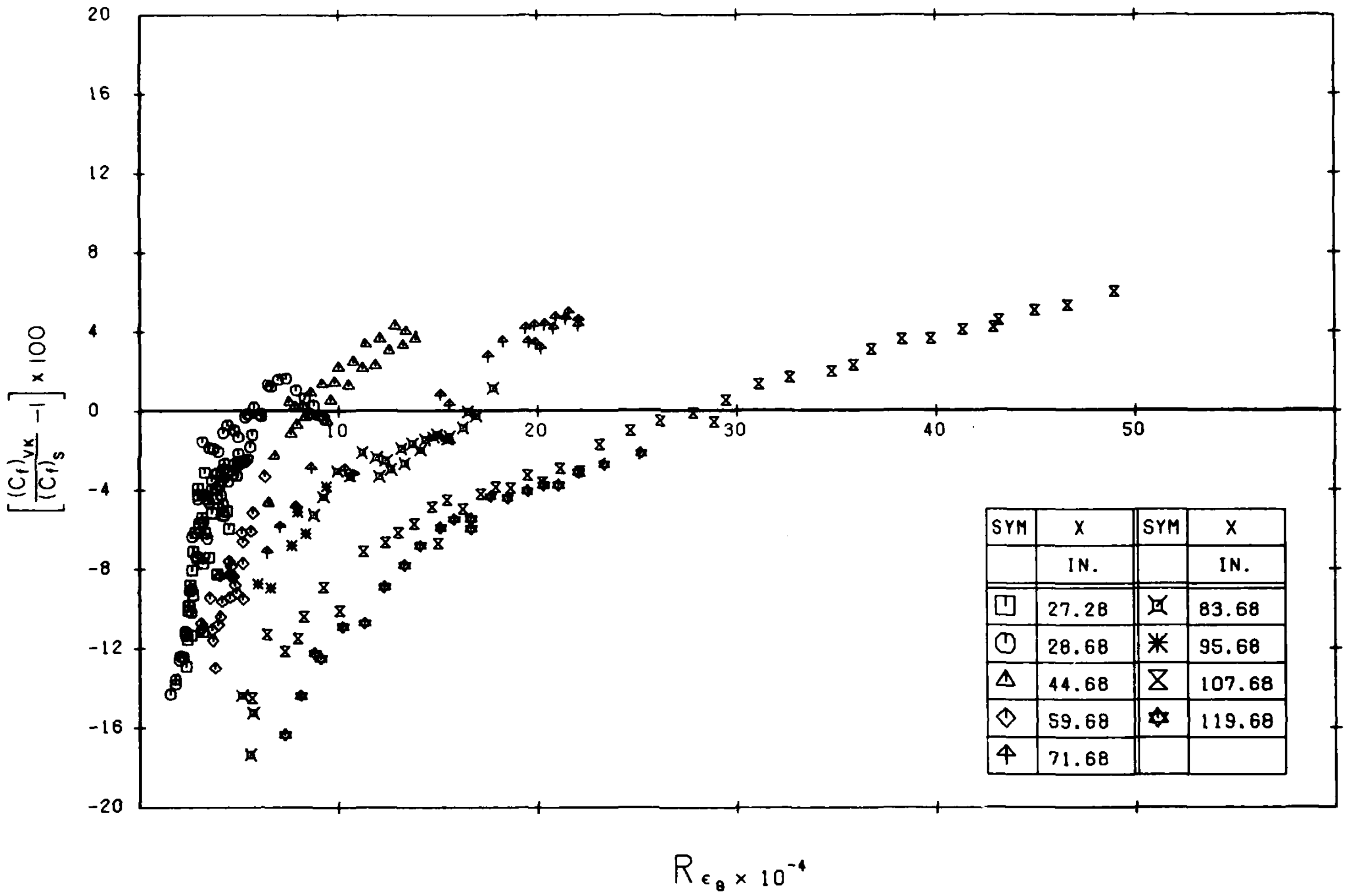


Figure 22. Percent Difference Between Von Karman Measurements and Shang Theory Versus Momentum Reynolds Number for Near Adiabatic Wall Temperature and $M_e = 2.88$

TABLE I
MEASURED SKIN FRICTION COEFFICIENTS

DATE= APRIL 5 1974 STATION= 1 X= 27.28

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 75.43 | 422.95 | 421.24 | 2.43 | 8.70 | 2.89 | 2.3907 | 3.9584 | 1.34246 | 1.26447 | 1.12138 | 2.64807 | 2.49425 | 2.21199 | 1.14653 | .96238 |
| 79.11 | 445.26 | 480.66 | 2.68 | 9.27 | 2.85 | 2.3370 | 3.9185 | 1.24498 | 1.24617 | 1.10597 | 2.53914 | 2.54178 | 2.25582 | 1.01016 | .83040 |
| 93.82 | 445.90 | 480.32 | 2.93 | 9.63 | 2.91 | 2.7248 | 4.5069 | 1.19678 | 1.11827 | 1.12366 | 2.48064 | 2.31791 | 2.32908 | 1.16134 | .92672 |
| 101.18 | 448.45 | 480.65 | 3.10 | 10.55 | 2.92 | 2.8993 | 4.7861 | 1.23874 | 1.13367 | 1.12654 | 2.57127 | 2.35317 | 2.33837 | 1.23940 | .98566 |
| 101.18 | 422.31 | 417.95 | 3.77 | 12.15 | 2.79 | 3.2000 | 5.5983 | 1.19972 | 1.10032 | 1.05845 | 2.28523 | 2.09763 | 2.01782 | 1.59668 | 1.46524 |
| 112.22 | 450.36 | 480.98 | 3.27 | 11.69 | 2.96 | 3.1661 | 5.1810 | 1.25687 | 1.14787 | 1.13789 | 2.63202 | 2.40375 | 2.39286 | 1.34589 | 1.05173 |
| 115.90 | 450.36 | 480.65 | 3.52 | 12.84 | 2.93 | 3.2761 | 5.4239 | 1.29214 | 1.17116 | 1.12257 | 2.68113 | 2.43011 | 2.32928 | 1.40620 | 1.12323 |
| 125.10 | 422.31 | 417.29 | 4.36 | 15.01 | 2.84 | 3.8958 | 6.7625 | 1.23418 | 1.09791 | 1.06899 | 2.38421 | 2.12096 | 2.06510 | 1.92091 | 1.72604 |
| 130.62 | 451.00 | 480.65 | 3.93 | 13.98 | 2.93 | 3.6603 | 6.0908 | 1.24254 | 1.10791 | 1.11858 | 2.58023 | 2.30066 | 2.32282 | 1.57184 | 1.25956 |
| 147.17 | 424.22 | 416.96 | 4.86 | 17.63 | 2.87 | 4.4992 | 7.7577 | 1.24329 | 1.09792 | 1.07785 | 2.43361 | 2.13874 | 2.09965 | 2.21041 | 1.95654 |

DATE= APRIL 9 1974 STATION= 1 X= 27.28

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 86.35 | 441.58 | 469.47 | 2.51 | 9.08 | 2.96 | 2.5375 | 4.1019 | 1.23516 | 1.22793 | 1.15133 | 2.58089 | 2.56579 | 2.40574 | 1.08530 | .83962 |
| 93.70 | 442.85 | 469.14 | 2.59 | 9.43 | 2.99 | 2.7194 | 4.3565 | 1.27554 | 1.19855 | 1.16313 | 2.68763 | 2.52539 | 2.45076 | 1.15719 | .87983 |
| 102.89 | 443.48 | 468.81 | 2.76 | 10.82 | 3.01 | 2.9576 | 4.7212 | 1.30493 | 1.24808 | 1.16826 | 2.76445 | 2.64401 | 2.47491 | 1.25424 | .94508 |
| 115.75 | 445.38 | 469.47 | 3.09 | 12.20 | 3.01 | 3.2865 | 5.2706 | 1.27208 | 1.21962 | 1.16322 | 2.69275 | 2.58171 | 2.46232 | 1.39833 | 1.05939 |

DATE= APRIL 12 1974 STATION= 1 X= 27.28

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 79.00 | 428.37 | 420.57 | 2.40 | 8.45 | 2.93 | 2.4377 | 3.9730 | 1.25734 | 1.22084 | 1.13931 | 2.49078 | 2.41731 | 2.25538 | 1.18096 | .97330 |
| 90.03 | 460.04 | 482.26 | 2.73 | 9.62 | 2.93 | 2.5621 | 4.0373 | 1.23524 | 1.21248 | 1.13623 | 2.54006 | 2.49125 | 2.33870 | 1.10156 | .87579 |
| 99.21 | 428.97 | 420.56 | 2.90 | 11.16 | 2.95 | 3.0161 | 4.9254 | 1.29195 | 1.24721 | 1.13982 | 2.57341 | 2.49027 | 2.27534 | 1.44313 | 1.18545 |
| 102.89 | 462.53 | 482.94 | 2.81 | 10.28 | 3.00 | 2.7927 | 4.4692 | 1.24316 | 1.19058 | 1.16578 | 2.60540 | 2.49521 | 2.44324 | 1.21008 | .92317 |
| 110.24 | 464.48 | 483.59 | 2.89 | 11.22 | 3.02 | 2.3535 | 4.6870 | 1.27377 | 1.22765 | 1.17567 | 2.70120 | 2.59121 | 2.48147 | 1.27395 | .95783 |

DATE= APRIL 16 1974 STATION= 1 X= 27.28

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 82.32 | 438.08 | 455.21 | 2.48 | 8.82 | 2.93 | 2.4595 | 4.0073 | 1.25873 | 1.22800 | 1.14133 | 2.57717 | 2.51426 | 2.33680 | 1.09507 | .87143 |
| 85.98 | 436.81 | 452.91 | 2.81 | 9.75 | 2.88 | 2.5910 | 4.3279 | 1.25551 | 1.20485 | 1.11134 | 2.52478 | 2.42098 | 2.23308 | 1.17749 | .97885 |
| 89.63 | 437.44 | 453.57 | 2.56 | 9.18 | 2.97 | 2.6603 | 4.2938 | 1.18930 | 1.19602 | 1.15360 | 2.45890 | 2.47279 | 2.33510 | 1.17534 | .91754 |
| 100.61 | 436.81 | 452.27 | 2.89 | 11.48 | 2.95 | 2.9760 | 4.8385 | 1.32382 | 1.27964 | 1.14541 | 2.72582 | 2.64083 | 2.36381 | 1.31882 | 1.03900 |
| 107.93 | 436.17 | 452.25 | 3.48 | 12.87 | 2.89 | 3.2178 | 5.4145 | 1.24097 | 1.20844 | 1.10421 | 2.50194 | 2.43636 | 2.22621 | 1.45747 | 1.21641 |
| 117.07 | 435.53 | 452.59 | 3.82 | 13.80 | 2.88 | 3.4863 | 5.9035 | 1.27186 | 1.16223 | 1.09608 | 2.56122 | 2.34042 | 2.20721 | 1.57792 | 1.32820 |
| 133.54 | 436.17 | 452.25 | 3.98 | 15.17 | 2.94 | 3.9132 | 6.5151 | 1.27812 | 1.16127 | 1.11843 | 2.62044 | 2.38088 | 2.23304 | 1.74323 | 1.41561 |
| 142.68 | 436.81 | 452.59 | 4.48 | 16.99 | 2.91 | 4.1767 | 7.0755 | 1.27544 | 1.15099 | 1.09313 | 2.58511 | 2.33287 | 2.22572 | 1.88306 | 1.57388 |
| 151.83 | 438.08 | 452.59 | 4.80 | 18.06 | 2.90 | 4.4155 | 7.5146 | 1.25336 | 1.12717 | 1.09228 | 2.53164 | 2.27676 | 2.20628 | 2.00265 | 1.68848 |

TABLE 1
MEASURED SKIN FRICTION COEFFICIENTS

DATE= MAY 15 1974 STATION= 1 X= 28.08

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 71.56 | 514.41 | 497.03 | 2.29 | 7.52 | 2.93 | 1.8156 | 2.9531 | 1.26333 | 1.25406 | 1.13760 | 2.44320 | 2.43502 | 2.20378 | .90815 | .76170 |
| 80.73 | 486.51 | 455.45 | 2.62 | 8.77 | 2.88 | 2.2014 | 3.5362 | 1.16520 | 1.22229 | 1.12229 | 2.22110 | 2.32793 | 2.13748 | 1.15438 | 1.00162 |
| 82.57 | 516.32 | 500.95 | 2.62 | 8.77 | 2.90 | 2.0675 | 3.3834 | 1.23476 | 1.23412 | 1.13326 | 2.41657 | 2.40753 | 2.21077 | 1.02596 | .86065 |
| 93.58 | 509.98 | 490.16 | 2.95 | 9.90 | 2.90 | 2.3669 | 3.8937 | 1.17225 | 1.19415 | 1.12791 | 2.27875 | 2.32134 | 2.19257 | 1.18656 | 1.00582 |
| 102.75 | 507.44 | 485.22 | 3.19 | 11.38 | 2.91 | 2.6015 | 4.2859 | 1.21275 | 1.22915 | 1.12689 | 2.36027 | 2.39218 | 2.19317 | 1.30840 | 1.10756 |
| 113.76 | 505.54 | 482.95 | 3.44 | 12.64 | 2.93 | 2.8733 | 4.7241 | 1.19503 | 1.22483 | 1.13018 | 2.33757 | 2.39367 | 2.20889 | 1.44237 | 1.21378 |
| 128.44 | 506.17 | 483.27 | 3.76 | 14.00 | 2.95 | 3.2098 | 5.2653 | 1.19055 | 1.19481 | 1.13365 | 2.34109 | 2.34947 | 2.22920 | 1.60297 | 1.33744 |
| 137.61 | 506.81 | 483.27 | 3.93 | 14.91 | 2.97 | 3.4129 | 5.5730 | 1.19307 | 1.19185 | 1.13865 | 2.36945 | 2.35517 | 2.25004 | 1.69799 | 1.40464 |
| 146.79 | 506.81 | 482.95 | 4.17 | 15.94 | 2.97 | 3.6272 | 5.9426 | 1.19382 | 1.17883 | 1.13634 | 2.36017 | 2.33064 | 2.24661 | 1.80485 | 1.49567 |
| 155.96 | 507.44 | 483.27 | 4.50 | 17.30 | 2.96 | 3.8407 | 6.3363 | 1.17719 | 1.17294 | 1.12629 | 2.31925 | 2.31087 | 2.22292 | 1.91364 | 1.60661 |
| 155.96 | 483.34 | 446.27 | 4.66 | 18.55 | 2.94 | 4.1219 | 6.8904 | 1.29280 | 1.20028 | 1.11283 | 2.45514 | 2.30823 | 2.14005 | 2.16826 | 1.88477 |
| 163.30 | 507.44 | 483.27 | 4.75 | 18.21 | 2.96 | 4.0147 | 6.6514 | 1.20947 | 1.16050 | 1.12346 | 2.37926 | 2.28294 | 2.21008 | 2.00855 | 1.69159 |
| 174.31 | 506.81 | 483.27 | 4.99 | 19.47 | 2.97 | 4.2729 | 7.0751 | 1.18463 | 1.15551 | 1.12463 | 2.33938 | 2.28177 | 2.22080 | 2.12727 | 1.76377 |
| 181.65 | 506.81 | 482.94 | 5.40 | 20.61 | 2.94 | 4.4536 | 7.4729 | 1.17984 | 1.13123 | 1.11025 | 2.31059 | 2.21549 | 2.17423 | 2.23946 | 1.81065 |
| 192.66 | 507.44 | 482.95 | 5.73 | 22.20 | 2.94 | 4.7066 | 7.9114 | 1.17492 | 1.13139 | 1.10714 | 2.29342 | 2.21540 | 2.16087 | 2.30516 | 2.03401 |
| 203.67 | 506.81 | 482.94 | 5.99 | 23.23 | 2.96 | 4.9576 | 8.2958 | 1.18331 | 1.12745 | 1.11292 | 2.34065 | 2.22080 | 2.19215 | 2.47597 | 2.10358 |
| 209.17 | 507.44 | 482.62 | 6.22 | 24.02 | 2.94 | 5.0567 | 8.5895 | 1.17426 | 1.10695 | 1.10271 | 2.29725 | 2.16165 | 2.15745 | 2.56296 | 2.21134 |
| 218.35 | 506.81 | 482.62 | 6.55 | 25.50 | 2.94 | 5.3135 | 9.0096 | 1.18364 | 1.10615 | 1.09773 | 2.31750 | 2.16165 | 2.14522 | 2.67512 | 2.32195 |
| 227.52 | 506.17 | 482.62 | 6.71 | 26.40 | 2.95 | 5.5266 | 9.3439 | 1.19069 | 1.10120 | 1.10070 | 2.33655 | 2.16094 | 2.15936 | 2.76834 | 2.38717 |
| 244.04 | 500.46 | 472.80 | 7.37 | 28.57 | 2.93 | 6.0125 | 10.2801 | 1.19405 | 1.07168 | 1.08879 | 2.32023 | 2.08245 | 2.11569 | 3.06695 | 2.69860 |
| 264.22 | 501.73 | 473.12 | 7.69 | 31.31 | 2.96 | 6.4402 | 10.9474 | 1.20783 | 1.09073 | 1.09618 | 2.36254 | 2.13349 | 2.14414 | 3.26903 | 2.84094 |
| 286.24 | 501.73 | 472.80 | 8.43 | 34.05 | 2.95 | 6.9557 | 11.9082 | 1.20399 | 1.06640 | 1.08834 | 2.34265 | 2.08013 | 2.12233 | 3.54260 | 3.10926 |
| 304.59 | 502.37 | 473.45 | 9.08 | 36.44 | 2.94 | 7.3738 | 12.7057 | 1.21553 | 1.04860 | 1.08119 | 2.36484 | 2.04008 | 2.10348 | 3.76485 | 3.33441 |
| 324.77 | 502.37 | 472.80 | 10.07 | 39.06 | 2.91 | 7.8634 | 13.7353 | 1.17420 | 1.01190 | 1.06581 | 2.26430 | 1.95133 | 2.05529 | 4.05535 | 3.67335 |
| 341.28 | 501.73 | 472.80 | 10.88 | 41.33 | 2.89 | 8.2771 | 14.6083 | 1.17482 | .98761 | 1.05433 | 2.25345 | 1.89435 | 2.02228 | 4.28662 | 3.94420 |
| 361.47 | 501.73 | 472.46 | 11.87 | 44.16 | 2.88 | 8.7623 | 15.6322 | 1.16138 | .96388 | 1.04245 | 2.21332 | 1.83693 | 1.98567 | 4.57007 | 4.27813 |
| 381.65 | 501.10 | 472.14 | 13.01 | 46.24 | 2.85 | 9.2706 | 16.7588 | 1.13626 | .92097 | 1.02802 | 2.14903 | 1.74182 | 1.94428 | 4.86970 | 4.65457 |

DATE= MAY 29 1974 STATION= 1 X= 28.08

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 58.90 | 506.49 | 491.85 | 1.84 | 6.26 | 2.91 | 1.5387 | 2.4637 | 1.30419 | 1.34695 | 1.15492 | 2.55269 | 2.63638 | 2.26053 | .76047 | .62359 |
| 69.94 | 509.03 | 496.44 | 2.26 | 7.39 | 2.89 | 1.8039 | 2.9453 | 1.24264 | 1.25576 | 1.13492 | 2.42137 | 2.44693 | 2.21148 | .89209 | .74749 |
| 79.14 | 510.93 | 502.02 | 2.51 | 8.42 | 2.90 | 2.0151 | 3.2940 | 1.22541 | 1.24356 | 1.13436 | 2.40636 | 2.44201 | 2.22757 | .98239 | .81778 |
| 80.98 | 472.89 | 441.96 | 2.51 | 9.00 | 2.91 | 2.2881 | 3.7429 | 1.21266 | 1.27667 | 1.13459 | 2.32913 | 2.45208 | 2.17918 | 1.19212 | 1.01529 |
| 88.34 | 502.69 | 485.61 | 2.76 | 9.57 | 2.91 | 2.2847 | 3.7447 | 1.23368 | 1.23825 | 1.13213 | 2.41791 | 2.41706 | 2.20992 | 1.13743 | .95507 |
| 99.39 | 498.88 | 480.03 | 2.93 | 10.70 | 2.95 | 2.5687 | 4.1710 | 1.23392 | 1.24566 | 1.14464 | 2.43353 | 2.45668 | 2.25744 | 1.27025 | 1.04586 |
| 110.43 | 495.08 | 474.78 | 3.35 | 12.18 | 2.93 | 2.8765 | 4.7348 | 1.20037 | 1.21412 | 1.12874 | 2.34883 | 2.37574 | 2.20868 | 1.43785 | 1.20955 |
| 128.83 | 496.35 | 474.78 | 3.60 | 14.34 | 2.99 | 3.2934 | 5.3437 | 1.23035 | 1.25090 | 1.14756 | 2.44628 | 2.48714 | 2.28172 | 1.62406 | 1.32533 |
| 136.20 | 496.35 | 474.78 | 3.94 | 15.03 | 2.96 | 3.4825 | 5.7172 | 1.19512 | 1.19651 | 1.13353 | 2.36148 | 2.36226 | 2.23791 | 1.72935 | 1.43802 |
| 143.56 | 496.35 | 474.78 | 4.02 | 16.39 | 2.98 | 3.6502 | 5.9576 | 1.20670 | 1.24594 | 1.14111 | 2.39851 | 2.47651 | 2.26814 | 1.80056 | 1.47848 |
| 154.60 | 496.35 | 474.78 | 4.35 | 17.17 | 2.98 | 3.9184 | 6.4297 | 1.19657 | 1.18915 | 1.13506 | 2.37536 | 2.36064 | 2.25327 | 1.93529 | 1.59967 |
| 154.60 | 472.25 | 434.08 | 4.86 | 18.57 | 2.90 | 4.2399 | 7.1931 | 1.29131 | 1.16395 | 1.09533 | 2.45137 | 2.20961 | 2.07934 | 2.26827 | 2.02711 |
| 161.96 | 496.98 | 474.78 | 4.69 | 18.34 | 2.96 | 4.0985 | 6.7902 | 1.19387 | 1.17441 | 1.12362 | 2.35642 | 2.31620 | 2.21603 | 2.03966 | 1.71342 |
| 171.17 | 496.35 | 474.78 | 4.86 | 19.38 | 2.97 | 4.3189 | 7.1377 | 1.19111 | 1.17495 | 1.12705 | 2.36080 | 2.32876 | 2.23382 | 2.13643 | 1.78142 |
| 180.37 | 496.35 | 474.78 | 5.28 | 20.83 | 2.95 | 4.5317 | 7.6045 | 1.17835 | 1.15695 | 1.11429 | 2.32042 | 2.27829 | 2.19428 | 2.26609 | 1.92256 |
| 191.41 | 496.35 | 474.78 | 5.61 | 22.32 | 2.95 | 4.8168 | 8.0763 | 1.17207 | 1.14901 | 1.11039 | 2.30701 | 2.26163 | 2.18562 | 2.39914 | 2.04368 |
| 198.77 | 496.35 | 474.78 | 5.86 | 23.22 | 2.95 | 4.9951 | 8.4044 | 1.18553 | 1.13636 | 1.10650 | 2.33065 | 2.23399 | 2.17527 | 2.49099 | 2.13192 |
| 207.98 | 496.35 | 474.78 | 6.20 | 24.60 | 2.94 | 5.2194 | 8.8275 | 1.18383 | 1.12873 | 1.10062 | 2.32200 | 2.21392 | 2.15878 | 2.60875 | 2.24947 |
| 217.18 | 496.35 | 474.12 | 6.53 | 25.96 | 2.93 | 5.4429 | 9.2490 | 1.17167 | 1.12101 | 1.09533 | 2.29191 | 2.19281 | 2.14258 | 2.73116 | 2.37258 |
| 226.38 | 495.08 | 474.12 | 6.70 | 26.88 | 2.94 | 5.6736 | 9.6212 | 1.17647 | 1.11490 | 1.09808 | 2.31235 | 2.19135 | 2.15829 | 2.82696 | 2.43904 |
| 239.26 | 488.10 | 460.99 | 7.29 | 29.16 | 2.93 | 6.1139 | 10.4887 | 1.20430 | 1.10046 | 1.08494 | 2.33520 | 2.13384 | 2.10376 | 3.12600 | 2.76569 |
| 259.51 | 488.10 | 460.39 | 7.62 | 31.10 | 2.95 | 6.5827 | 11.2284 | 1.20720 | 1.09074 | 1.09226 | 2.35899 | 2.13141 | 2.13438 | 3.33995 | 2.91546 |

TABLE I
MEASURED SKIN FRICTION COEFFICIENTS

DATE= APRIL 25 1974     STATION= 1     X= 23.68

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 79.26 | 422.82 | 419.25 | 2.34 | 7.70 | 2.95 | 2.6105 | 4.2432 | 1.20947 | 1.13105 | 1.14352 | 2.42112 | 2.26414 | 2.28910 | 1.24124 | 1.00787 |
| 88.48 | 447.55 | 473.20 | 2.34 | 8.05 | 3.02 | 2.6497 | 4.1883 | 1.12275 | 1.14742 | 1.17878 | 2.38649 | 2.43894 | 2.50560 | 1.11978 | .83271 |
| 99.54 | 449.45 | 472.54 | 2.67 | 8.62 | 3.01 | 2.9498 | 4.7081 | 1.06561 | 1.05230 | 1.16731 | 2.25060 | 2.22249 | 2.46539 | 1.26068 | .95271 |
| 105.07 | 423.46 | 417.92 | 3.26 | 10.33 | 2.91 | 3.4181 | 5.7111 | 1.17649 | 1.03140 | 1.11196 | 2.32760 | 2.04056 | 2.19994 | 1.64761 | 1.39143 |
| 108.76 | 451.36 | 472.54 | 2.67 | 9.53 | 3.07 | 3.1628 | 4.9527 | 1.17126 | 1.11485 | 1.19219 | 2.51495 | 2.39384 | 2.55990 | 1.33493 | .97352 |
| 119.82 | 451.99 | 472.55 | 3.09 | 10.69 | 3.04 | 3.4768 | 5.5405 | 1.16390 | 1.06844 | 1.17058 | 2.47151 | 2.26880 | 2.48569 | 1.48535 | 1.11470 |
| 127.19 | 452.63 | 472.88 | 3.34 | 11.85 | 3.02 | 3.6785 | 5.9068 | 1.14590 | 1.08287 | 1.16144 | 2.42312 | 2.28985 | 2.45598 | 1.57899 | 1.19903 |
| 130.88 | 423.46 | 417.59 | 4.01 | 13.22 | 2.92 | 4.2064 | 7.0835 | 1.21389 | 1.01368 | 1.10413 | 2.41864 | 2.00980 | 2.18913 | 2.02465 | 1.71965 |
| 136.41 | 453.26 | 472.55 | 3.67 | 12.76 | 3.01 | 3.9327 | 6.3800 | 1.10372 | 1.04926 | 1.14918 | 2.32902 | 2.20412 | 2.41403 | 1.70229 | 1.31463 |
| 145.62 | 453.26 | 472.88 | 3.84 | 13.57 | 3.02 | 4.1766 | 6.7610 | 1.13811 | 1.04559 | 1.15230 | 2.40220 | 2.20692 | 2.43217 | 1.79827 | 1.37918 |
| 154.84 | 453.83 | 472.22 | 4.09 | 14.50 | 3.02 | 4.4191 | 7.1734 | 1.16307 | 1.03397 | 1.14845 | 2.46075 | 2.17825 | 2.41941 | 1.91096 | 1.47348 |
| 154.84 | 424.72 | 417.27 | 4.68 | 15.86 | 2.93 | 4.9080 | 8.3026 | 1.25294 | .99854 | 1.09989 | 2.48641 | 1.98156 | 2.18270 | 2.36813 | 2.01871 |
| 165.90 | 453.89 | 472.22 | 4.51 | 15.89 | 3.00 | 4.7306 | 7.7693 | 1.14873 | 1.01753 | 1.13542 | 2.40549 | 2.13075 | 2.37761 | 2.05780 | 1.61391 |
| 173.27 | 453.89 | 471.89 | 4.84 | 16.90 | 2.98 | 4.9425 | 8.1958 | 1.16841 | 1.00417 | 1.12399 | 2.43127 | 2.08952 | 2.33883 | 2.16473 | 1.72508 |
| 186.18 | 453.89 | 471.56 | 5.09 | 17.83 | 3.00 | 5.2810 | 8.7390 | 1.16757 | .98561 | 1.12700 | 2.43970 | 2.05948 | 2.35492 | 2.30490 | 1.82535 |
| 191.71 | 453.89 | 471.56 | 5.26 | 18.88 | 2.99 | 5.4313 | 9.0082 | 1.19707 | 1.00255 | 1.12444 | 2.43974 | 2.09354 | 2.34807 | 2.37197 | 1.88395 |
| 202.76 | 454.53 | 470.90 | 5.68 | 19.91 | 2.98 | 5.7276 | 9.5769 | 1.18000 | .97299 | 1.11503 | 2.44976 | 2.02000 | 2.31487 | 2.52198 | 2.03121 |

DATE= MAY 16 1974     STATION= 2     X= 44.68

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 161.47 | 488.59 | 450.21 | 5.66 | 20.05 | 2.83 | 6.4767 | 11.5726 | 1.08782 | 1.11403 | 1.02500 | 2.02123 | 2.06993 | 1.90452 | 3.53224 | 3.39677 |
| 205.50 | 511.41 | 484.33 | 6.57 | 24.50 | 2.89 | 7.5888 | 13.3415 | .98792 | 1.09643 | 1.04595 | 1.90018 | 2.10889 | 2.01180 | 3.89775 | 3.56261 |
| 214.68 | 511.41 | 484.59 | 6.82 | 25.54 | 2.90 | 7.9058 | 13.9060 | .99206 | 1.08820 | 1.04580 | 1.90995 | 2.09505 | 2.01343 | 4.05922 | 3.70861 |
| 225.69 | 510.14 | 484.59 | 7.16 | 26.89 | 2.90 | 8.3170 | 14.6595 | .99624 | 1.07804 | 1.04393 | 1.92153 | 2.07930 | 2.01351 | 4.25311 | 3.88667 |
| 234.86 | 510.14 | 484.27 | 7.49 | 28.15 | 2.90 | 8.6417 | 15.2860 | 1.00360 | 1.06982 | 1.04018 | 1.93275 | 2.06028 | 2.00319 | 4.42859 | 4.06765 |
| 240.37 | 489.22 | 449.55 | 7.91 | 30.24 | 2.87 | 9.3845 | 16.8122 | 1.13441 | 1.07550 | 1.02622 | 2.13300 | 2.02225 | 1.92959 | 5.06997 | 4.83053 |
| 242.20 | 506.34 | 475.76 | 7.32 | 29.42 | 2.89 | 9.0000 | 16.0086 | 1.04229 | 1.06388 | 1.03409 | 1.99090 | 2.03215 | 1.97525 | 4.69247 | 4.36970 |
| 266.06 | 506.34 | 475.44 | 8.24 | 32.05 | 2.91 | 9.8039 | 17.3224 | 1.04152 | 1.06338 | 1.04291 | 2.00646 | 2.04858 | 2.00914 | 5.07147 | 4.65137 |
| 286.24 | 506.97 | 475.10 | 9.07 | 35.27 | 2.90 | 10.5114 | 18.7567 | 1.03697 | 1.05145 | 1.03210 | 1.98591 | 2.01365 | 1.97659 | 5.47906 | 5.10515 |
| 306.42 | 506.97 | 475.10 | 9.57 | 37.43 | 2.91 | 11.1997 | 19.9753 | 1.02214 | 1.03750 | 1.03337 | 1.96352 | 1.99301 | 1.98509 | 5.82009 | 5.40371 |
| 324.77 | 506.97 | 475.10 | 10.23 | 40.41 | 2.90 | 11.8447 | 21.2403 | 1.02407 | 1.03471 | 1.02768 | 1.96346 | 1.98386 | 1.97038 | 6.16701 | 5.76793 |
| 344.95 | 505.97 | 475.10 | 10.73 | 42.68 | 2.91 | 12.5287 | 22.4536 | 1.03372 | 1.02429 | 1.02873 | 1.99686 | 1.96911 | 1.97765 | 6.50586 | 6.06643 |
| 365.14 | 505.97 | 474.77 | 11.40 | 45.46 | 2.91 | 13.2274 | 23.8008 | 1.04396 | 1.01483 | 1.02493 | 2.01630 | 1.94684 | 1.96824 | 6.88029 | 6.44677 |
| 383.49 | 506.34 | 474.12 | 11.96 | 48.22 | 2.91 | 13.6826 | 25.0504 | 1.02370 | 1.01184 | 1.02220 | 1.97689 | 1.94259 | 1.96249 | 7.22379 | 6.78946 |
| 403.00 | 501.26 | 464.23 | 12.48 | 50.49 | 2.91 | 14.6503 | 25.5023 | 1.11067 | 1.00412 | 1.01987 | 2.12057 | 1.91714 | 1.94721 | 7.73997 | 7.33347 |
| 422.02 | 501.90 | 464.29 | 13.06 | 53.34 | 2.91 | 15.3772 | 27.8237 | 1.07405 | .99924 | 1.01995 | 2.05274 | 1.90976 | 1.94920 | 8.12491 | 7.69382 |

TABLE I
MEASURED SKIN FRICTION COEFFICIENTS

DATE= MAY 31 1974 STATION= 2 X= 44.63

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 163.40 | 475.25 | 437.59 | 5.32 | 13.43 | 2.95 | 5.7807 | 11.5939 | 1.11731 | 1.13933 | 1.04713 | 2.11016 | 2.15080 | 1.97674 | 3.64154 | 3.38420 |
| 193.77 | 501.25 | 473.39 | 5.48 | 23.32 | 2.93 | 7.5195 | 13.0005 | .99599 | 1.12838 | 1.06582 | 1.94730 | 2.20616 | 2.08383 | 3.77790 | 3.34076 |
| 206.13 | 500.61 | 473.39 | 6.31 | 24.24 | 2.92 | 7.4994 | 13.5926 | .99599 | 1.10755 | 1.05819 | 1.94333 | 2.15883 | 2.06262 | 3.93105 | 3.51026 |
| 217.18 | 500.51 | 477.73 | 6.73 | 25.05 | 2.91 | 8.2144 | 14.3810 | .99428 | 1.10508 | 1.05182 | 1.93182 | 2.14709 | 2.04363 | 4.15322 | 3.74231 |
| 226.22 | 500.61 | 477.49 | 6.98 | 27.07 | 2.92 | 8.6003 | 15.0349 | 1.01531 | 1.09140 | 1.05367 | 1.97754 | 2.12573 | 2.05226 | 4.34040 | 3.89701 |
| 237.42 | 476.52 | 437.09 | 7.56 | 28.89 | 2.90 | 9.5944 | 17.0602 | 1.13958 | 1.09416 | 1.03520 | 2.15681 | 2.07084 | 1.95926 | 5.15161 | 4.83999 |
| 239.26 | 493.54 | 465.90 | 7.31 | 28.39 | 2.92 | 9.1708 | 16.0894 | 1.04793 | 1.07599 | 1.05055 | 2.03238 | 2.08682 | 2.03746 | 4.68197 | 4.23535 |
| 263.19 | 494.91 | 465.90 | 7.97 | 31.37 | 2.93 | 9.9964 | 17.5801 | 1.04728 | 1.06384 | 1.04865 | 2.03187 | 2.06401 | 2.03454 | 5.11323 | 4.63491 |
| 283.44 | 494.91 | 465.57 | 8.64 | 34.19 | 2.92 | 10.7305 | 18.9726 | 1.05283 | 1.05334 | 1.04311 | 2.03941 | 2.04030 | 2.02049 | 5.50113 | 5.02149 |
| 301.84 | 494.91 | 465.57 | 9.05 | 35.70 | 2.94 | 11.3748 | 20.0836 | 1.05287 | 1.05705 | 1.04511 | 2.04632 | 2.05445 | 2.03124 | 5.81178 | 5.28100 |
| 322.09 | 494.91 | 466.25 | 9.72 | 39.55 | 2.93 | 12.1041 | 21.4814 | 1.05004 | 1.04691 | 1.04004 | 2.03752 | 2.03144 | 2.01812 | 6.19826 | 5.66895 |
| 344.17 | 495.54 | 465.25 | 10.30 | 41.83 | 2.94 | 12.8587 | 22.8456 | 1.07738 | 1.02929 | 1.03941 | 2.09267 | 1.99928 | 2.01894 | 6.58554 | 6.02369 |
| 356.90 | 495.54 | 465.92 | 10.96 | 44.07 | 2.92 | 13.4046 | 23.9991 | 1.06770 | 1.01370 | 1.03090 | 2.06410 | 1.95970 | 1.99295 | 6.90183 | 6.39180 |
| 379.14 | 494.91 | 465.59 | 11.71 | 47.23 | 2.92 | 14.1599 | 25.4997 | 1.05666 | 1.00660 | 1.02472 | 2.05798 | 1.94209 | 1.97705 | 7.30156 | 6.81518 |

DATE= MAY 3 1974 STATION= 3 X= 59.68

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 65.85 | 476.26 | 484.33 | 2.48 | 6.37 | 2.79 | 3.7693 | 6.7097 | 1.12658 | 1.01063 | 1.01469 | 2.17464 | 1.95083 | 1.95865 | 1.82317 | 1.67241 |
| 73.17 | 476.90 | 487.27 | 2.48 | 7.16 | 2.85 | 4.1476 | 7.1708 | 1.16462 | 1.08732 | 1.04555 | 2.30441 | 2.15147 | 2.06882 | 1.93879 | 1.69407 |
| 80.49 | 450.75 | 433.82 | 2.81 | 8.64 | 2.84 | 4.9210 | 8.6534 | 1.23445 | 1.11711 | 1.02742 | 2.36472 | 2.13993 | 1.96812 | 2.47929 | 2.27592 |
| 84.15 | 477.54 | 490.87 | 2.81 | 8.30 | 2.86 | 4.7218 | 8.1881 | 1.20375 | 1.07233 | 1.04394 | 2.40704 | 2.13539 | 2.07885 | 2.18168 | 1.89986 |
| 91.46 | 472.44 | 478.76 | 3.06 | 9.32 | 2.86 | 5.1877 | 9.0432 | 1.21042 | 1.08061 | 1.03899 | 2.39129 | 2.13484 | 2.05261 | 2.44640 | 2.15863 |

DATE= MAY 6 1974 STATION= 3 X= 59.68

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 63.17 | 471.63 | 479.69 | 2.24 | 6.30 | 2.83 | 3.6760 | 6.3915 | 1.10309 | 1.10512 | 1.03657 | 2.16859 | 2.16084 | 2.02679 | 1.74582 | 1.55244 |
| 68.58 | 472.27 | 482.64 | 2.40 | 7.12 | 2.83 | 3.9636 | 6.8976 | 1.18349 | 1.13786 | 1.03672 | 2.33559 | 2.23610 | 2.03734 | 1.86514 | 1.65165 |
| 77.61 | 446.13 | 434.19 | 2.65 | 8.37 | 2.85 | 4.8152 | 8.4106 | 1.17344 | 1.14704 | 1.03534 | 2.26881 | 2.20648 | 1.99162 | 2.41651 | 2.19420 |
| 79.41 | 472.90 | 485.23 | 2.74 | 8.36 | 2.84 | 4.5412 | 7.9244 | 1.23159 | 1.12865 | 1.03555 | 2.43691 | 2.23323 | 2.04902 | 2.11110 | 1.86181 |
| 90.24 | 467.30 | 474.13 | 3.23 | 9.28 | 2.82 | 5.2201 | 9.2733 | 1.18188 | 1.03291 | 1.01570 | 2.30118 | 2.01114 | 1.97762 | 2.49731 | 2.27902 |
| 97.46 | 465.89 | 469.88 | 3.23 | 10.43 | 2.87 | 5.6147 | 9.9090 | 1.23366 | 1.11747 | 1.03754 | 2.43472 | 2.20540 | 2.04766 | 2.66161 | 2.35610 |

DATE= MAY 17 1974 STATION= 3 X= 59.68

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 60.55 | 514.67 | 495.54 | 1.98 | 6.14 | 2.88 | 3.1098 | 5.2440 | 1.27598 | 1.24238 | 1.07227 | 2.46296 | 2.39810 | 2.06975 | 1.57018 | 1.37171 |
| 71.56 | 516.53 | 497.50 | 2.48 | 7.16 | 2.84 | 3.6425 | 6.2885 | 1.20153 | 1.12779 | 1.04520 | 2.29239 | 2.15171 | 1.99414 | 1.86019 | 1.68328 |
| 80.73 | 517.84 | 500.78 | 2.81 | 8.30 | 2.84 | 4.0721 | 7.0810 | 1.25309 | 1.12284 | 1.03811 | 2.39379 | 2.14498 | 1.98312 | 2.06945 | 1.88377 |
| 82.57 | 484.24 | 453.31 | 2.72 | 8.76 | 2.87 | 4.5442 | 7.8358 | 1.26065 | 1.17260 | 1.05033 | 2.39294 | 2.22580 | 1.99371 | 2.39204 | 2.17301 |
| 89.91 | 511.50 | 490.96 | 2.97 | 9.32 | 2.87 | 4.5685 | 7.8851 | 1.25680 | 1.14182 | 1.04926 | 2.41669 | 2.19560 | 2.01763 | 2.32189 | 2.08410 |
| 102.75 | 509.60 | 487.03 | 3.30 | 10.57 | 2.89 | 5.2003 | 8.9700 | 1.22328 | 1.11945 | 1.05212 | 2.37039 | 2.16036 | 2.03042 | 2.64362 | 2.36286 |
| 111.93 | 505.60 | 483.10 | 3.63 | 11.70 | 2.88 | 5.7035 | 9.9124 | 1.24399 | 1.10267 | 1.04421 | 2.39498 | 2.12290 | 2.01036 | 2.90785 | 2.62498 |
| 124.77 | 506.43 | 483.75 | 3.96 | 12.84 | 2.90 | 6.3006 | 10.9451 | 1.22167 | 1.07633 | 1.04634 | 2.36286 | 2.08176 | 2.02376 | 3.19729 | 2.87169 |

TABLE I
MEASURED SKIN FRICTION COEFFICIENTS

DATE= JUNE 4 1974 STATION= 3 X= 59.63

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 60.92 | 515.26 | 497.08 | 2.02 | 6.02 | 2.87 | 3.1262 | 5.2905 | 1.26750 | 1.19921 | 1.06783 | 2.44291 | 2.31128 | 2.05807 | 1.57811 | 1.38564 |
| 70.15 | 515.83 | 499.38 | 2.27 | 7.05 | 2.89 | 3.5613 | 6.0314 | 1.27348 | 1.13837 | 1.06901 | 2.48062 | 2.32459 | 2.07418 | 1.78044 | 1.55407 |
| 81.23 | 518.42 | 505.94 | 2.61 | 7.96 | 2.89 | 4.0628 | 6.9135 | 1.22301 | 1.13771 | 1.06513 | 2.38776 | 2.22123 | 2.07953 | 2.00406 | 1.74673 |
| 81.23 | 480.57 | 450.81 | 2.61 | 8.30 | 2.83 | 4.5116 | 7.7205 | 1.22301 | 1.15514 | 1.05976 | 2.33735 | 2.20764 | 2.02540 | 2.35449 | 2.10820 |
| 90.46 | 511.48 | 491.50 | 2.94 | 9.32 | 2.88 | 4.5895 | 7.8837 | 1.24217 | 1.14634 | 1.05432 | 2.39803 | 2.21302 | 2.03537 | 2.32098 | 2.06679 |
| 101.54 | 508.95 | 486.91 | 3.19 | 10.36 | 2.90 | 5.1418 | 8.8139 | 1.24196 | 1.13043 | 1.05972 | 2.40378 | 2.19246 | 2.05531 | 2.59853 | 2.29666 |

DATE= MAY 7 1974 STATION= 4 X= 71.68

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 286.24 | 470.26 | 452.72 | 9.06 | 31.37 | 2.90 | 18.2692 | 33.5647 | .85938 | .92359 | .98708 | 1.67029 | 1.79509 | 1.91849 | 9.16232 | 8.66085 |
| 286.24 | 470.26 | 452.72 | 9.06 | 31.37 | 2.90 | 18.2692 | 33.5647 | .85938 | .92359 | .98708 | 1.67029 | 1.79509 | 1.91849 | 9.16232 | 8.66085 |
| 306.42 | 471.54 | 453.05 | 9.64 | 33.08 | 2.90 | 19.4075 | 35.7164 | .88126 | .90134 | .98608 | 1.71307 | 1.75211 | 1.91682 | 9.74885 | 9.22958 |
| 321.10 | 525.08 | 424.89 | 10.30 | 36.42 | 2.89 | 17.5139 | 32.2261 | .98969 | .95802 | .98454 | 1.74988 | 1.69388 | 1.74078 | 11.28183 | 11.74071 |
| 322.94 | 472.17 | 452.39 | 10.22 | 35.60 | 2.90 | 20.3709 | 37.6468 | .86221 | .90517 | .98190 | 1.67139 | 1.75467 | 1.90342 | 10.28658 | 9.80671 |
| 343.12 | 472.17 | 452.39 | 10.80 | 38.13 | 2.90 | 21.5684 | 39.9269 | .89515 | .90288 | .98087 | 1.73712 | 1.75214 | 1.90347 | 10.87953 | 10.37818 |
| 361.47 | 471.54 | 452.39 | 11.47 | 40.07 | 2.90 | 22.7138 | 42.2533 | .86541 | .88544 | .97604 | 1.67794 | 1.71677 | 1.89244 | 11.45613 | 10.99056 |
| 383.49 | 472.81 | 451.73 | 12.05 | 42.48 | 2.90 | 23.9212 | 44.5030 | .92940 | .88034 | .97670 | 1.80166 | 1.70655 | 1.89336 | 12.10942 | 11.62145 |
| 398.17 | 525.72 | 424.89 | 12.63 | 45.27 | 2.90 | 21.4249 | 39.7293 | 1.05328 | .92424 | .97872 | 1.86552 | 1.63697 | 1.73348 | 13.79267 | 14.44052 |
| 401.83 | 518.71 | 440.61 | 12.88 | 45.38 | 2.89 | 22.0347 | 41.0318 | .95756 | .90422 | .97423 | 1.73664 | 1.63993 | 1.76690 | 13.24235 | 13.53709 |
| 427.52 | 519.35 | 440.28 | 13.54 | 48.00 | 2.90 | 23.3063 | 43.3964 | .95464 | .83499 | .97523 | 1.73380 | 1.62546 | 1.77130 | 14.31230 | 14.30603 |
| 445.87 | 518.71 | 440.28 | 14.04 | 50.17 | 2.90 | 24.2842 | 45.2446 | 1.02264 | .89196 | .97523 | 1.86376 | 1.62298 | 1.77449 | 14.55636 | 14.90545 |
| 460.55 | 519.35 | 440.28 | 14.54 | 52.01 | 2.90 | 25.0056 | 46.6927 | 1.02305 | .88778 | .97308 | 1.87024 | 1.61349 | 1.76853 | 15.02352 | 15.43552 |
| 478.90 | 521.26 | 439.95 | 15.04 | 54.43 | 2.91 | 25.8077 | 48.2050 | 1.04107 | .88984 | .97325 | 1.88979 | 1.61526 | 1.76666 | 15.56650 | 16.03838 |

DATE= MAY 8 1974 STATION= 4 X= 71.68

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 91.74 | 462.34 | 470.03 | 3.25 | 9.16 | 2.83 | 6.4082 | 11.4773 | .99934 | 1.00304 | .99913 | 1.95372 | 1.96095 | 1.95342 | 3.04473 | 2.76936 |
| 100.92 | 459.79 | 465.51 | 3.50 | 10.18 | 2.84 | 7.0579 | 12.6326 | .98463 | 1.00655 | 1.00131 | 1.92316 | 1.97211 | 1.96283 | 3.35864 | 3.06822 |
| 111.93 | 457.24 | 459.94 | 3.93 | 11.43 | 2.85 | 7.8401 | 14.0651 | .97306 | 1.00106 | 1.00093 | 1.90466 | 1.95946 | 1.95920 | 3.75577 | 3.44227 |
| 124.77 | 457.87 | 459.94 | 4.09 | 12.35 | 2.89 | 8.6444 | 15.4002 | .96753 | .97988 | 1.01131 | 1.91055 | 1.93494 | 1.99700 | 4.11006 | 3.70805 |
| 157.80 | 461.05 | 420.55 | 5.50 | 17.27 | 2.84 | 10.7512 | 19.7072 | 1.01980 | .97994 | .98056 | 1.88523 | 1.81332 | 1.81448 | 5.93993 | 5.88399 |
| 236.70 | 465.52 | 420.00 | 8.00 | 26.75 | 2.86 | 15.5520 | 28.8340 | .99324 | .94560 | .97347 | 1.83886 | 1.75066 | 1.80226 | 8.67412 | 8.68659 |
| 297.25 | 460.42 | 449.14 | 9.58 | 33.05 | 2.89 | 19.5312 | 35.1942 | .88389 | .90981 | .97734 | 1.71749 | 1.77389 | 1.90673 | 9.65111 | 9.17297 |
| 317.43 | 459.79 | 448.82 | 10.17 | 35.37 | 2.89 | 20.8172 | 38.6412 | .87964 | .90205 | .97705 | 1.71611 | 1.76165 | 1.90832 | 10.26251 | 9.75321 |
| 317.43 | 471.26 | 420.00 | 10.42 | 36.36 | 2.88 | 20.1546 | 37.5884 | 1.03924 | .92021 | .97093 | 1.92348 | 1.70316 | 1.79705 | 11.36827 | 11.45523 |
| 337.61 | 460.42 | 448.81 | 10.92 | 37.42 | 2.89 | 22.0462 | 41.1535 | .91012 | .88003 | .97137 | 1.77266 | 1.71407 | 1.89196 | 10.91202 | 10.45804 |
| 357.80 | 461.05 | 448.16 | 11.50 | 40.29 | 2.89 | 23.2393 | 43.4322 | .91306 | .88591 | .97085 | 1.77792 | 1.72507 | 1.89346 | 11.53450 | 11.07066 |

TABLE I
MEASURED SKIN FRICTION COEFFICIENTS

DATE= MAY 20 1974 STATION= 4 X= 71.58

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 159.63 | 476.75 | 437.15 | 5.47 | 17.91 | 2.85 | 10.3625 | 18.3656 | 1.00754 | 1.02471 | .99804 | 1.87633 | 1.90631 | 1.84033 | 5.06334 | 5.53676 |
| 238.53 | 477.33 | 436.50 | 7.87 | 27.15 | 2.87 | 15.0997 | 27.7637 | .99399 | .97356 | .98260 | 1.87218 | 1.82453 | 1.84147 | 8.22105 | 8.06757 |
| 319.27 | 477.33 | 436.82 | 10.35 | 36.83 | 2.88 | 19.8862 | 35.9446 | .93074 | .93636 | .97527 | 1.84532 | 1.76183 | 1.83504 | 10.77631 | 10.64080 |
| 339.45 | 497.57 | 465.33 | 10.68 | 38.00 | 2.90 | 19.8525 | 36.5847 | .86285 | .92665 | .98485 | 1.65303 | 1.77526 | 1.83076 | 10.36252 | 9.96789 |
| 357.80 | 496.94 | 465.06 | 11.26 | 40.29 | 2.90 | 20.3067 | 38.6352 | .87656 | .92027 | .98240 | 1.67376 | 1.76354 | 1.83258 | 10.30416 | 10.51531 |
| 381.65 | 496.31 | 464.41 | 12.01 | 42.90 | 2.90 | 22.2661 | 41.2818 | .91259 | .90589 | .97957 | 1.74382 | 1.73598 | 1.87718 | 11.61459 | 11.23703 |
| 396.33 | 489.37 | 453.57 | 12.51 | 44.07 | 2.90 | 23.5382 | 43.8029 | .93556 | .88448 | .97610 | 1.78264 | 1.66532 | 1.85930 | 12.45334 | 12.16246 |

DATE= MAY 9 1974 STATION= 5 X= 83.68

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 62.39 | 465.45 | 480.85 | 2.49 | 5.63 | 2.75 | 5.1413 | 9.4034 | 1.24899 | 1.07119 | .95826 | 2.40278 | 2.06073 | 1.84349 | 2.44798 | 2.32663 |
| 152.29 | 460.35 | 466.78 | 5.30 | 16.13 | 2.84 | 12.0653 | 22.2434 | 1.05631 | .95540 | .96641 | 2.06884 | 1.87172 | 1.89330 | 5.73456 | 5.39766 |
| 159.63 | 459.72 | 466.45 | 5.55 | 17.26 | 2.84 | 12.6399 | 23.3592 | 1.07708 | .96481 | .96470 | 2.11137 | 1.89129 | 1.89106 | 6.00055 | 5.65707 |
| 168.81 | 459.72 | 466.45 | 5.89 | 18.39 | 2.84 | 13.3306 | 24.7200 | 1.06956 | .95798 | .96164 | 2.09569 | 1.87706 | 1.88423 | 6.33127 | 5.99195 |
| 179.82 | 460.99 | 466.45 | 6.22 | 19.42 | 2.84 | 14.0913 | 26.1483 | 1.05780 | .94258 | .96193 | 2.07315 | 1.84733 | 1.88526 | 6.70722 | 6.35063 |
| 188.99 | 460.99 | 466.12 | 6.47 | 20.57 | 2.85 | 14.7613 | 27.3832 | 1.05316 | .94610 | .96329 | 2.07358 | 1.85760 | 1.89132 | 7.01775 | 6.63048 |
| 198.17 | 460.39 | 466.12 | 6.88 | 21.80 | 2.84 | 15.4578 | 28.8597 | 1.03564 | .93580 | .95646 | 2.02716 | 1.83173 | 1.87217 | 7.37142 | 7.03098 |
| 209.17 | 461.63 | 465.46 | 7.21 | 23.20 | 2.84 | 16.2321 | 30.3270 | 1.04836 | .93666 | .95658 | 2.05195 | 1.83331 | 1.87231 | 7.76021 | 7.40756 |
| 218.35 | 461.63 | 465.79 | 7.46 | 23.87 | 2.85 | 16.8954 | 31.5558 | 1.03985 | .92090 | .95773 | 2.04001 | 1.80664 | 1.87302 | 8.05368 | 7.66736 |

DATE= JUNE 12 1974 STATION= 5 X= 83.68

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 79.14 | 521.51 | 500.02 | 3.75 | 8.17 | 2.64 | 5.5699 | 10.7351 | 1.13474 | .87430 | .89648 | 2.02292 | 1.55862 | 1.59816 | 3.05775 | 3.30581 |
| 80.98 | 520.25 | 501.31 | 3.58 | 8.51 | 2.69 | 5.6890 | 10.7647 | 1.29209 | .94299 | .91883 | 2.34271 | 1.70975 | 1.66594 | 3.05658 | 3.18987 |
| 125.15 | 506.45 | 479.13 | 4.32 | 12.83 | 2.84 | 8.7702 | 15.8649 | 1.11036 | 1.03496 | .98336 | 2.09866 | 1.89344 | 1.85861 | 4.59318 | 4.39604 |
| 132.52 | 506.45 | 479.12 | 4.49 | 13.76 | 2.85 | 9.2449 | 16.6830 | 1.14379 | 1.01904 | .98751 | 2.17063 | 1.93389 | 1.87405 | 4.82223 | 4.58540 |
| 143.56 | 505.82 | 479.45 | 4.74 | 14.54 | 2.87 | 9.9705 | 17.3385 | 1.10231 | .99474 | .99285 | 2.10564 | 1.90016 | 1.89655 | 5.15806 | 4.85820 |
| 152.76 | 506.45 | 478.80 | 5.16 | 16.10 | 2.86 | 10.5773 | 19.2047 | 1.11130 | 1.00325 | .98273 | 2.11000 | 1.90485 | 1.86590 | 5.51780 | 5.27649 |
| 161.96 | 505.82 | 478.80 | 5.33 | 17.14 | 2.87 | 11.1763 | 20.2082 | 1.11316 | 1.01254 | .98904 | 2.13814 | 1.93443 | 1.88954 | 5.78801 | 5.47792 |
| 173.01 | 506.45 | 478.80 | 5.82 | 18.51 | 2.86 | 11.9009 | 21.7264 | 1.09926 | .99092 | .97842 | 2.08849 | 1.88265 | 1.85890 | 6.20425 | 5.96169 |
| 180.37 | 506.45 | 478.80 | 6.16 | 19.76 | 2.85 | 12.3950 | 22.7630 | 1.07114 | .99375 | .97198 | 2.02910 | 1.88250 | 1.84126 | 6.48092 | 6.28294 |
| 191.41 | 505.82 | 478.14 | 6.49 | 20.99 | 2.85 | 13.1299 | 24.1448 | 1.04779 | .98554 | .97154 | 1.98743 | 1.86935 | 1.84279 | 6.85709 | 6.64790 |
| 200.61 | 506.45 | 479.13 | 6.82 | 21.92 | 2.85 | 13.7080 | 25.2849 | 1.05370 | .96995 | .96870 | 1.99834 | 1.83952 | 1.83714 | 7.15406 | 6.95877 |
| 209.82 | 505.82 | 478.14 | 7.16 | 22.92 | 2.85 | 14.3322 | 26.5211 | 1.02700 | .95751 | .96570 | 1.94560 | 1.81396 | 1.82948 | 7.49418 | 7.32009 |
| 219.02 | 505.82 | 478.14 | 7.49 | 24.43 | 2.85 | 14.9314 | 27.7093 | 1.05340 | .96544 | .96305 | 1.99457 | 1.82802 | 1.82348 | 7.81161 | 7.65618 |
| 228.22 | 505.19 | 478.14 | 7.90 | 25.33 | 2.84 | 15.5687 | 29.0569 | 1.05227 | .94266 | .95701 | 1.93841 | 1.78128 | 1.80840 | 8.15250 | 8.05211 |
| 239.26 | 500.17 | 468.35 | 8.07 | 26.68 | 2.86 | 16.4740 | 30.6202 | 1.08346 | .95237 | .96313 | 2.04693 | 1.79927 | 1.81960 | 8.71075 | 8.56986 |
| 259.51 | 500.17 | 469.00 | 8.57 | 28.52 | 2.87 | 17.7636 | 32.9598 | 1.06284 | .93658 | .96674 | 2.01853 | 1.77874 | 1.83603 | 9.33195 | 9.11713 |

TABLE I
MEASURED SKIN FRICTION COEFFICIENTS

DATE= MAY 10 1974 STATION= 6 X= 95.63

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 66.06 | 473.33 | 481.34 | 2.28 | 6.30 | 2.84 | 5.9595 | 10.3512 | 1.07371 | 1.06907 | .99194 | 2.11173 | 2.10260 | 1.95331 | 2.61401 | 2.53367 |
| 73.39 | 474.01 | 483.30 | 2.61 | 6.99 | 2.82 | 6.5906 | 11.8302 | 1.03346 | 1.01342 | .97602 | 2.03136 | 1.98237 | 1.91920 | 3.12200 | 2.85632 |
| 82.57 | 475.96 | 435.31 | 2.70 | 8.38 | 2.83 | 7.9699 | 14.1258 | 1.13283 | 1.11122 | .99775 | 2.20752 | 2.14422 | 1.94496 | 3.92552 | 3.57305 |
| 86.24 | 474.55 | 487.55 | 2.95 | 8.25 | 2.85 | 7.6434 | 13.6873 | 1.08351 | 1.01193 | .98343 | 2.14504 | 2.00428 | 1.94783 | 3.55253 | 3.21217 |
| 93.58 | 471.45 | 476.13 | 3.28 | 9.41 | 2.85 | 8.3378 | 15.1039 | 1.14052 | 1.03969 | .97931 | 2.23777 | 2.03576 | 1.92129 | 3.97150 | 3.64278 |
| 106.42 | 473.63 | 471.85 | 3.46 | 10.44 | 2.88 | 9.3988 | 15.7812 | 1.13356 | 1.02428 | .99223 | 2.25136 | 2.02364 | 1.95541 | 4.47578 | 4.04459 |

DATE= MAY 13 1974 STATION= 7 X= 107.43

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 60.55 | 508.02 | 485.95 | 2.41 | 6.51 | 2.75 | 5.6279 | 10.3377 | 1.14540 | 1.12268 | .93133 | 2.11341 | 2.07194 | 1.72003 | 2.46942 | 2.37535 |
| 63.72 | 509.23 | 483.58 | 2.58 | 7.43 | 2.80 | 5.3785 | 11.5553 | 1.00579 | 1.14152 | .95353 | 1.89014 | 2.14309 | 1.79016 | 3.32155 | 3.20544 |
| 75.90 | 473.73 | 439.80 | 3.08 | 6.68 | 2.76 | 7.9538 | 14.7954 | .99504 | 1.07282 | .92575 | 1.81696 | 1.95703 | 1.64874 | 4.30394 | 4.47643 |
| 80.73 | 511.82 | 493.16 | 3.15 | 8.57 | 2.76 | 7.3113 | 13.5540 | .97137 | 1.05132 | .92773 | 1.80614 | 1.95481 | 1.72435 | 3.52931 | 3.61552 |
| 89.91 | 503.58 | 483.07 | 3.41 | 9.83 | 2.78 | 8.2615 | 15.2835 | 1.00383 | 1.07687 | .93407 | 1.86830 | 2.00424 | 1.73347 | 4.36444 | 4.33729 |
| 100.92 | 501.04 | 475.49 | 3.74 | 10.96 | 2.80 | 9.2681 | 17.1418 | 1.03132 | 1.05735 | .93729 | 1.92380 | 1.97236 | 1.74841 | 4.90466 | 4.86317 |
| 108.26 | 497.67 | 471.89 | 4.24 | 11.39 | 2.75 | 10.0329 | 19.9132 | 1.01309 | 1.01401 | .91433 | 1.86144 | 1.86867 | 1.68618 | 5.35070 | 5.53586 |
| 122.94 | 497.67 | 471.89 | 4.49 | 13.26 | 2.81 | 11.2632 | 20.3619 | 1.02771 | 1.01181 | .93470 | 1.92194 | 1.89220 | 1.74800 | 5.35204 | 5.92335 |
| 135.78 | 499.51 | 472.21 | 4.39 | 14.62 | 2.80 | 12.3612 | 23.1530 | .99042 | .98284 | .92886 | 1.84929 | 1.83514 | 1.73436 | 6.54632 | 6.56795 |
| 143.12 | 498.51 | 471.89 | 5.24 | 15.54 | 2.80 | 12.9907 | 24.3751 | 1.01533 | .98195 | .92824 | 1.89969 | 1.83437 | 1.73404 | 6.96025 | 6.91069 |
| 152.29 | 498.51 | 471.56 | 5.57 | 15.44 | 2.80 | 13.7794 | 25.9325 | 1.01164 | .96285 | .92605 | 1.88934 | 1.79823 | 1.72950 | 7.30443 | 7.36066 |
| 155.96 | 473.22 | 432.92 | 5.99 | 19.17 | 2.77 | 14.9781 | 28.6952 | 1.10374 | .98372 | .90613 | 2.00412 | 1.77655 | 1.63642 | 8.53925 | 9.05873 |
| 163.30 | 498.51 | 472.21 | 5.90 | 17.70 | 2.81 | 14.7103 | 27.6919 | .98896 | .95952 | .92745 | 1.85292 | 1.79776 | 1.73767 | 7.76325 | 7.80000 |
| 172.48 | 499.14 | 471.56 | 6.24 | 19.97 | 2.81 | 15.4668 | 29.1953 | .99363 | .96166 | .92535 | 1.86343 | 1.79315 | 1.73124 | 8.19372 | 8.26700 |
| 181.65 | 499.73 | 471.56 | 6.73 | 20.35 | 2.80 | 16.2488 | 30.9644 | .99411 | .94933 | .91434 | 1.84884 | 1.76667 | 1.70140 | 8.66920 | 8.88298 |
| 192.66 | 500.41 | 471.56 | 7.07 | 21.46 | 2.80 | 17.1387 | 32.6534 | .96480 | .94006 | .91630 | 1.79710 | 1.75103 | 1.70677 | 9.14013 | 9.35047 |
| 201.83 | 500.41 | 471.56 | 7.40 | 22.61 | 2.80 | 17.9119 | 34.2072 | .98474 | .93565 | .91472 | 1.83444 | 1.74300 | 1.70400 | 9.55137 | 9.79173 |
| 211.01 | 501.68 | 471.22 | 7.82 | 23.87 | 2.80 | 18.6331 | 35.7609 | .95690 | .92865 | .90966 | 1.77565 | 1.72324 | 1.68798 | 10.00359 | 10.34634 |
| 222.02 | 502.31 | 470.30 | 8.15 | 25.12 | 2.80 | 19.5076 | 37.4356 | .96201 | .92505 | .91092 | 1.78670 | 1.71806 | 1.69181 | 10.48138 | 10.83077 |
| 231.19 | 503.53 | 470.30 | 8.65 | 25.52 | 2.79 | 20.2300 | 39.1039 | .94202 | .91676 | .90312 | 1.74032 | 1.69365 | 1.66846 | 10.95264 | 11.45306 |
| 236.70 | 479.48 | 432.59 | 8.90 | 28.20 | 2.79 | 22.1416 | 43.0617 | 1.06913 | .93015 | .89789 | 1.93584 | 1.68419 | 1.62579 | 12.62840 | 13.56410 |
| 240.37 | 500.41 | 461.08 | 8.90 | 27.85 | 2.80 | 21.1581 | 40.8740 | .99079 | .92405 | .90483 | 1.82009 | 1.69749 | 1.66229 | 11.67251 | 12.27507 |
| 262.39 | 498.51 | 461.08 | 9.56 | 30.16 | 2.81 | 23.0881 | 44.5209 | .96421 | .90784 | .90661 | 1.78064 | 1.67652 | 1.67425 | 12.62711 | 13.21449 |
| 282.57 | 500.41 | 461.08 | 10.23 | 31.97 | 2.81 | 24.6286 | 47.6733 | .94431 | .88491 | .90631 | 1.74284 | 1.63321 | 1.67271 | 13.52339 | 14.18331 |
| 300.92 | 500.41 | 461.08 | 10.89 | 34.62 | 2.81 | 26.1442 | 50.7677 | .93683 | .88693 | .90395 | 1.72905 | 1.63696 | 1.66839 | 14.35536 | 15.10345 |
| 313.76 | 480.12 | 432.59 | 11.64 | 38.15 | 2.80 | 28.8541 | 56.7109 | 1.02200 | .90029 | .89184 | 1.85429 | 1.63347 | 1.61814 | 16.44240 | 17.81132 |
| 321.10 | 500.41 | 460.75 | 11.64 | 37.48 | 2.81 | 27.8095 | 54.2038 | .91735 | .88565 | .90096 | 1.69189 | 1.63341 | 1.66166 | 15.29067 | 16.15952 |
| 341.28 | 500.41 | 460.42 | 12.30 | 39.97 | 2.81 | 29.4543 | 57.5018 | .89717 | .88022 | .90049 | 1.65592 | 1.62462 | 1.66137 | 16.19289 | 17.12752 |
| 361.47 | 500.41 | 460.42 | 12.89 | 42.24 | 2.82 | 31.0787 | 60.6601 | .88822 | .87430 | .90203 | 1.64329 | 1.61753 | 1.66883 | 17.04540 | 17.98276 |
| 391.65 | 501.04 | 459.77 | 13.63 | 44.67 | 2.82 | 32.6722 | 63.9790 | .89704 | .86463 | .89333 | 1.65646 | 1.59662 | 1.65068 | 17.99640 | 19.08422 |
| 396.33 | 480.75 | 432.92 | 14.22 | 47.18 | 2.82 | 35.8640 | 70.6530 | .99284 | .85960 | .89429 | 1.81356 | 1.57018 | 1.63354 | 20.30892 | 21.30469 |
| 398.17 | 493.43 | 447.33 | 14.30 | 45.95 | 2.82 | 34.7513 | 69.3743 | .92254 | .83904 | .89515 | 1.69074 | 1.53772 | 1.64055 | 19.49707 | 20.93106 |
| 422.02 | 492.80 | 447.65 | 14.88 | 50.40 | 2.83 | 36.7393 | 72.1394 | .94520 | .86649 | .89892 | 1.74262 | 1.59582 | 1.65555 | 20.47422 | 21.82842 |
| 440.37 | 492.17 | 447.65 | 15.46 | 52.47 | 2.83 | 38.3095 | 75.3030 | .93364 | .85891 | .89864 | 1.73142 | 1.58436 | 1.65763 | 21.29117 | 22.69822 |
| 458.72 | 492.80 | 447.65 | 16.21 | 54.41 | 2.83 | 39.7723 | 78.4735 | .93597 | .84461 | .89504 | 1.72297 | 1.55480 | 1.64762 | 22.17437 | 23.76774 |
| 478.90 | 493.43 | 447.33 | 16.38 | 55.71 | 2.83 | 41.3493 | 81.6913 | .92979 | .83770 | .89441 | 1.71060 | 1.54135 | 1.64570 | 23.10631 | 24.60991 |
| 478.90 | 480.75 | 433.24 | 16.96 | 58.06 | 2.83 | 42.8805 | 84.9959 | .98187 | .84733 | .89137 | 1.79906 | 1.55255 | 1.63323 | 24.19125 | 26.17010 |
| 499.08 | 492.17 | 446.99 | 17.54 | 59.45 | 2.83 | 43.1462 | 85.3745 | .92848 | .83584 | .89357 | 1.71099 | 1.54026 | 1.64665 | 24.03446 | 25.50757 |
| 521.10 | 492.17 | 446.99 | 18.21 | 62.07 | 2.83 | 44.9306 | 88.9541 | .92155 | .83161 | .89388 | 1.70033 | 1.53439 | 1.64927 | 24.99721 | 26.62265 |
| 539.45 | 490.90 | 446.34 | 18.87 | 65.13 | 2.83 | 46.6014 | 92.4743 | .93022 | .83463 | .89202 | 1.71688 | 1.54046 | 1.64637 | 25.69204 | 27.53836 |
| 550.46 | 480.12 | 433.90 | 19.12 | 56.72 | 2.84 | 48.9586 | 97.2231 | .96700 | .83327 | .89231 | 1.78164 | 1.53526 | 1.64403 | 27.39801 | 29.53007 |

TABLE I
MEASURED SKIN FRICTION COEFFICIENTS

DATE= MAY 14 1974 STATION= 8 X= 119.68

| PO PSIA | TO DEG R | TW DEG R | PW PSIA | PP PSIA | ME | RE THETA *10**-4 | REX *10**-7 | (CF)G *10**3 | (CF)P *10**3 | (CF)VK *10**3 | FC(CF)G *10**3 | FC(CF)P *10**3 | FC(CF)VK *10**3 | FRT*RET *10**-4 | FRX*REX *10**-7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 73.39 | 518.95 | 497.01 | 3.18 | 7.78 | 2.69 | 7.2936 | 13.3060 | 1.01681 | .99123 | .88077 | 1.84527 | 1.79885 | 1.59839 | 3.93629 | 4.13543 |
| 82.57 | 520.22 | 500.94 | 3.43 | 9.05 | 2.72 | 8.1077 | 15.3653 | 1.06935 | 1.03562 | .89178 | 1.96321 | 1.90129 | 1.63721 | 4.30415 | 4.44307 |
| 82.57 | 488.51 | 455.09 | 3.26 | 9.04 | 2.75 | 8.3084 | 16.5324 | 1.09807 | 1.05522 | .90677 | 2.00390 | 1.92577 | 1.65479 | 4.83486 | 4.97253 |
| 91.74 | 513.24 | 488.83 | 3.68 | 9.96 | 2.74 | 9.1061 | 17.1959 | 1.04704 | 1.02354 | .89996 | 1.92500 | 1.88180 | 1.65460 | 4.87426 | 5.00648 |
| 102.75 | 510.71 | 484.57 | 4.02 | 10.86 | 2.76 | 10.1909 | 19.2196 | 1.04872 | .98854 | .90507 | 1.93478 | 1.82375 | 1.66976 | 5.45426 | 5.57568 |
| 113.76 | 508.17 | 480.97 | 4.52 | 12.24 | 2.75 | 11.3142 | 21.5530 | 1.01154 | .96919 | .89548 | 1.85750 | 1.77972 | 1.64437 | 6.09728 | 6.32521 |
| 124.77 | 508.80 | 481.29 | 4.77 | 13.39 | 2.78 | 12.2967 | 23.2737 | 1.02525 | .97564 | .90588 | 1.89728 | 1.80548 | 1.67639 | 6.57873 | 6.73016 |
| 135.78 | 508.80 | 481.63 | 5.10 | 14.86 | 2.79 | 13.3083 | 25.1853 | 1.04399 | .98847 | .90872 | 1.93946 | 1.83632 | 1.68816 | 7.08800 | 7.22042 |
| 144.95 | 510.07 | 481.63 | 5.35 | 15.69 | 2.80 | 14.0943 | 26.6287 | 1.03107 | .97641 | .91251 | 1.91979 | 1.81803 | 1.69905 | 7.50611 | 7.61651 |
| 155.96 | 509.44 | 481.63 | 5.69 | 16.81 | 2.81 | 15.1201 | 28.5758 | 1.00607 | .96456 | .91418 | 1.87944 | 1.80190 | 1.70778 | 8.01696 | 8.11062 |
| 161.47 | 486.61 | 447.24 | 5.94 | 18.51 | 2.80 | 16.6557 | 31.7159 | 1.08656 | .99649 | .90743 | 1.99583 | 1.83037 | 1.66680 | 9.21006 | 9.54792 |
| 163.30 | 509.44 | 481.30 | 5.94 | 17.72 | 2.81 | 15.7912 | 29.8891 | 1.01512 | .96261 | .91353 | 1.89684 | 1.79674 | 1.70701 | 8.37555 | 8.48390 |
| 172.48 | 509.44 | 480.97 | 6.44 | 18.53 | 2.79 | 16.6651 | 31.8643 | 1.02152 | .92255 | .90227 | 1.89755 | 1.71371 | 1.67604 | 8.89712 | 9.15795 |
| 183.49 | 509.44 | 481.63 | 6.61 | 19.79 | 2.82 | 17.6253 | 33.4679 | 1.01431 | .93850 | .91264 | 1.89990 | 1.75789 | 1.70944 | 9.32035 | 9.44855 |
| 192.66 | 509.44 | 481.29 | 7.03 | 20.91 | 2.81 | 18.4787 | 35.2935 | 1.01526 | .92483 | .90641 | 1.89590 | 1.72703 | 1.69264 | 9.80742 | 10.03258 |
| 203.67 | 509.44 | 480.97 | 7.45 | 22.39 | 2.81 | 19.4832 | 37.3480 | 1.00132 | .92352 | .90355 | 1.86927 | 1.72311 | 1.68585 | 10.35557 | 10.63934 |
| 212.84 | 509.44 | 481.29 | 7.78 | 23.46 | 2.81 | 20.3152 | 39.0289 | 1.00365 | .91638 | .90198 | 1.88266 | 1.71044 | 1.68355 | 10.78726 | 11.10313 |
| 220.18 | 508.17 | 480.32 | 8.12 | 24.36 | 2.80 | 21.0646 | 40.6341 | 1.00361 | .90662 | .89778 | 1.88168 | 1.68973 | 1.67325 | 11.19713 | 11.59030 |
| 231.19 | 508.17 | 480.55 | 8.45 | 25.95 | 2.81 | 22.0493 | 42.5440 | .99369 | .91530 | .89889 | 1.85596 | 1.70954 | 1.67889 | 11.68842 | 12.07490 |
| 242.20 | 503.10 | 471.15 | 8.87 | 27.34 | 2.80 | 23.3680 | 45.2434 | 1.02739 | .90693 | .89609 | 1.90804 | 1.68432 | 1.66420 | 12.56835 | 13.10434 |
| 262.39 | 503.73 | 471.80 | 9.62 | 29.85 | 2.80 | 25.1717 | 48.3540 | 1.02337 | .89724 | .89279 | 1.91133 | 1.66598 | 1.65771 | 13.53978 | 14.18163 |

TABLE II

SKIN FRICTION COEFFICIENTS USING DIFFERENT PRESTON TUBE EQUATIONS

| $R_{e_\theta} \times 10^{-4}$ | $(C_f)_Y \times 10^3$ | $(C_f)_{HK} \times 10^3$ | $(C_f)_A \times 10^3$ | $(C_f)_p \times 10^3$ | $(C_f)_{VD} \times 10^3$ | $\frac{(C_f)_p-(C_f)_{VD}}{(C_f)_{VD}} \times 10$ |
|---|---|---|---|---|---|---|
| 2.3370 | 1.26530 | 1.29337 | 1.117686 | 1.24617 | 1.26037 | -1.13 |
| 3.2761 | 1.117585 | 1.21583 | 1.111981 | 1.117116 | 1.118410 | -1.09 |
| 4.1767 | 1.13721 | 1.19045 | 1.12423 | 1.15099 | 1.15568 | -0.41 |
| 4.4155 | 1.10844 | 1.16309 | 1.10912 | 1.12717 | 1.14798 | -1.81 |
| 4.9210 | 1.06721 | 1.08666 | 1.06298 | 1.07233 | 1.14501 | 0.09 |
| 5.6147 | 1.10622 | 1.13675 | 1.10919 | 1.11747 | 1.12156 | 0.62 |
| 6.3785 | 1.12831 | 1.14275 | 1.15336 | 1.14152 | 1.13328 | 0.80 |
| 8.1077 | 1.00834 | 1.02855 | 1.06906 | 1.03562 | 1.10666 | 0.83 |
| 8.3378 | 1.02386 | 1.04868 | 1.04636 | 1.03969 | 1.06006 | -4.12 |
| 8.6417 | 1.01883 | 1.08143 | 1.10727 | 1.06982 | 1.06884 | -0.36 |
| 9.3988 | 1.00443 | 1.03286 | 1.03528 | 1.02428 | 1.03786 | -3.14 |
| 11.1763 | 0.96869 | 1.01196 | 1.05512 | 1.01254 | 1.03401 | -3.77 |
| 11.1997 | 0.97336 | 1.04444 | 1.09129 | 1.03750 | 1.03106 | -2.08 |
| 11.2632 | 0.97134 | 1.00668 | 1.05564 | 1.01181 | 1.04513 | -2.84 |
| 13.1299 | 0.93319 | 0.98223 | 1.03838 | 0.98554 | 1.01437 | -3.15 |
| 13.3083 | 0.94325 | 0.98085 | 1.03895 | 0.98847 | 1.02421 | -1.92 |
| 13.2274 | 0.94313 | 1.01914 | 1.07774 | 1.01483 | 1.00674 | -1.31 |
| 14.6503 | 0.92540 | 1.00462 | 1.07665 | 1.00412 | 0.99588 | 0.73 |
| 14.9314 | 0.90738 | 0.96041 | 1.02495 | 0.96544 | 0.99686 | -3.19 |
| 16.6557 | 0.93799 | 0.98565 | 1.06190 | 0.99649 | 1.00000 | -4.10 |
| 18.2692 | 0.85977 | 0.92090 | 0.98579 | 0.92359 | 0.95352 | -3.37 |
| 20.3709 | 0.83579 | 0.89935 | 0.97500 | 0.90517 | 0.94065 | -3.97 |
| 22.0493 | 0.85123 | 0.90342 | 0.98618 | 0.91530 | 0.95103 | -3.49 |
| 22.1416 | 0.85067 | 0.90906 | 1.02249 | 0.93015 | 0.96987 | -0.35 |
| 48.9586 | 0.72639 | 0.80079 | 0.95610 | 0.83327 | 0.86233 | -3.76 |

# APPENDIX A

## THEORETICAL SKIN FRICTION COEFFICIENTS

The measured skin friction coefficients were compared with the theoretical calculations of Van Driest[11] and [14], the work of Wilson[10], and the semi-empirical method of Spalding-Chi[6] and the Spalding-Chi method presented by Komar[15]. The measurements were also compared with Shang's et al.[12] computer code; however its details are not presented because of its complex form. In Shang's code the skin friction coefficients is basically the same as Van Driest's value.

The skin friction coefficient equations used in this report are briefly outlined below. The Van Driest theory was taken from Reference 14 and is written slightly different than the form found in Van Driest's original paper[11]. This particular form was chosen because it lends itself more readily to hand calculations. It is reproduced here as it appears in Reference 14, namely;

$$(C_f)_{VD} = \frac{\left[\sin^{-1}\left(\dfrac{2A_1^2 - B_1}{\sqrt{B_1^2 + 4A_1^2}}\right) + \sin^{-1}\left(\dfrac{B_1}{\sqrt{B_1^2 + 4A_1^2}}\right)\right]^2}{r\left(\frac{\gamma-1}{2}\right)M_e^2\left[17.08\,\log \bar{R}_{e_\theta})^2 + 25.11\,(\log \bar{R}_{e_\theta}) + 6.012\right]} \qquad (A.1)$$

where

$$A_1 = M_e\sqrt{r\left(\frac{\gamma-1}{2}\right)\frac{T_e}{T_w}} \qquad (A.2)$$

$$B_1 = A_1^2 + \frac{T_e}{T_w} - 1 \qquad (A.3)$$

and

$$\bar{R}_{e_\theta} = \sqrt{\frac{T_e}{T_w}}\left[\frac{1 + \dfrac{220}{T_w\left(10^{9/T_w}\right)}}{1 + \dfrac{220}{T_e\left(10^{9/T_e}\right)}}\right] R_{e_\theta} \qquad (A.4)$$



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Wilson's skin friction coefficient equation is given in Reference 10 as

$$(C_f)_w = \frac{\alpha^2}{(\ln R_{e_\theta} + \beta)^2} \tag{A.5}$$

where

$$\alpha = \frac{0.55484}{\sqrt{\sigma}} \sqrt{\frac{T_e}{T_w}} \sin^{-1} \sqrt{\sigma} \tag{A.6}$$

$$\beta = 1.54246 + \ln \left(\frac{\mu_e}{\mu_w}\right) \tag{A.7}$$

and

$$\sigma = \frac{\gamma-1}{2} M_e^2 \Big/ 1 + \frac{\gamma-1}{2} M_e^2 \tag{A.8}$$

The Spalding-Chi skin friction coefficient was calculated from References 6 and 15. Both methods are semi-empirical and yield the same results. The method outlined below is that of Komar[15] which consists of a least squares curve fit to the tabulated data presented by Spalding-Chi in Reference 6. Both these methods are difficult to use; Reference 6 because of the necessity to interpolate between the tabulated values and Komar's closed form equation because of its numerical series form with complex coefficients. Between the two methods, Komar's method is preferred; the skin friction coefficient becomes

$$(C_f)_{SC} = \left(\frac{1}{F_c}\right) \exp \left[ \sum_{j=1}^{10} g_j' \left( \ln F_{R\theta} \cdot R_{e_\theta} \right)^{j-1} \right] \tag{A.9}$$

where

$$a_o = T_w/T_e \tag{A.10}$$

$$b_o = 1 + r\left(\frac{\gamma-1}{2}\right) M_e^{\,2} - \frac{T_w}{T_e} \tag{A·11}$$

$$c_o = -r\left(\frac{\gamma-1}{2}\right) M_e^{\,2} \tag{A·12}$$

$$\frac{1}{F_c} = \left[\frac{1}{\sqrt{-C_o}}\left\{\sin^{-1}\left(\frac{-b_o - 2C_o}{\sqrt{b_o^2 - 4a_o c_o}}\right) - \sin^{-1}\left(\frac{-b_o}{\sqrt{b_o^2 - 4a_o c_o}}\right)\right\}\right]^2 \tag{A.13}$$

and

$$F_{R\theta} = \frac{(T_{aw}/T_e)^{0.772}}{(T_w/T_e)^{1.474}} \tag{A.14}$$

The coefficients in Equation A.9 were determined by Komar[15] and are tabulated below.

| $j$ | $g'_j$ |
|---|---|
| 1 | -8.1597880 |
| 2 | 3.8659884 |
| 3 | -0.86304234 |
| 4 | -0.22725503 |
| 5 | 0.14047119 |
| 6 | -0.029148057 |
| 7 | 0.0032405621 |
| 8 | $-2.0526747 \times 10^{-4}$ |
| 9 | $6.9816431 \times 10^{-6}$ |
| 10 | $-9.8965784 \times 10^{-8}$ |

In each of the above three methods the assumptions are that we have an adiabatic wall and since its for a flat plate, the pressure gradient is zero. All methods take into account the compressibility effect.

# APPENDIX B

## ERROR ANALYSIS IN SKIN FRICTION MEASUREMENTS

An error analysis in the measuring methods used in obtaining the skin friction coefficients will be presented. The original measurements were made with a shear stress balance. This balance was calibrated statically in the range of 0 to 6.94 grams by both the contractor and the Flight Dynamics Laboratory. The calibration is of the form

$$F = \left(\frac{dF}{dE}\right)E + F_o \tag{B.1}$$

where dF/dE is the balance sensitivity in gm/volt, $F_o$ is the null output in volts, and E is the balance linearity in percent of full scale output. The procedure was to apply a known weight ($F_i$) in grams on the floating element of the balance and recording its electrical output ($E_i$) in volts. The method of least squares was then applied to determine both balance sensitivity and its null output. The mathematical expressions used for this purpose were

$$\frac{dF}{dE} = \frac{n \sum_{i=1}^{n} E_i F_i - \sum_{i=1}^{n} E_i \sum_{i=1}^{n} F_i}{n \sum_{i=1}^{n} E_i^2 - \left(\sum_{i=1}^{n} E_i\right)^2} \tag{B.2}$$

and

$$F_o = \frac{\sum_{i=1}^{n} E_i^2 \sum_{i=1}^{n} F_i - \sum_{i=1}^{n} E_i \sum_{i=1}^{n} E_i F_i}{n \sum_{i=1}^{n} E_i^2 - \left(\sum_{i=1}^{n} E_i\right)^2} \tag{B.3}$$

where "N" is equal to the total number of points recorded during the calibration process. The balance linearity is defined as

$$\varepsilon = \frac{F - F_i}{F_{F.S.O.}} \times 100 \qquad (B.4)$$

where F is obtained from Equation B.1, $F_i$ is the corresponding calibration weight in grams, and $F_{F.S.O.}$ is the balance full scale output, i.e., 6.94 grams.

At the Flight Dynamics Laboratory the balance was calibrated in both the vertical and horizontal position since it was to be employed in both modes.

These calibrations are tabulated below:

| $F_i$ | Contractor (Vertical) | AFFDL (Vertical) | AFFDL (Horizontal) | r.m.s. of Three Calibration |
|---|---|---|---|---|
| | $E_i$ | $E_i$ | $E_i$ | $E_i$ |
| gm | volts | volts | volts | volts |
| 0 | 0 | 0 | 0 | 0 |
| .001 | .0007 | --- | --- | .0007 |
| .002 | .0014 | --- | --- | .0014 |
| .005 | .0036 | --- | --- | .0036 |
| .010 | .0072 | --- | --- | .0072 |
| .020 | .0145 | --- | --- | .0145 |
| .050 | .0361 | --- | --- | .0361 |
| .060 | --- | --- | --- | --- |
| .069 | --- | --- | --- | --- |
| .100 | .0723 | --- | --- | .0723 |
| .200 | .1444 | --- | --- | .1444 |
| .500 | .3612 | .3600 | .3556 | .3589 |
| .600 | --- | --- | --- | --- |
| .694 | --- | --- | --- | --- |
| 1.00 | .7226 | .7218 | .7239 | .7228 |
| 1.50 | --- | 1.0828 | 1.0595 | 1.0712 |
| 2.00 | 1.4453 | 1.4453 | 1.4440 | 1.4449 |
| 2.50 | --- | 1.8058 | 1.7995 | 1.8027 |
| 3.00 | --- | 2.1673 | 2.1628 | 2.1651 |
| 3.50 | --- | 2.5273 | 2.5248 | 2.5261 |
| 4.00 | --- | 2.8918 | 2.8761 | 2.8840 |
| 4.50 | --- | 3.2513 | 3.2326 | 3.2420 |
| 5.00 | 3.6131 | 3.6123 | 3.5946 | 3.6067 |
| 5.50 | --- | 3.9723 | 3.9616 | 3.9670 |
| 6.00 | 4.3355 | --- | --- | 4.3355 |
| 6.94 | 5.0149 | --- | --- | 5.0149 |

The results of the calibrations are presented in the following table and indicate that the balance has excellent calibration repeatability with linearities well within one half of one percent of full scale output.

| Organization | $\frac{dF}{dE}$ (Sensitivity) | $F_o$ (Null Output) | $\varepsilon$ (Linearity) |
|---|---|---|---|
| | gm/volt | gm | % of F.S.O. |
| Contractor (Vertical) | 1.3839 | $2.429 \times 10^{-5}$ | - .003 |
| AFFDL (Vertical) | 1.3840 | $7.1444 \times 10^{-4}$ | .040 |
| AFFDL (Horizontal) | 1.3886 | $3.4672 \times 10^{-3}$ | - .360 |
| r.m.s. Average | 1.3852 | $1.5148 \times 10^{-3}$ | - .210 |

The percent difference resulting from various calibration have been calculated. These calculations are in percent of full scale output and are arbitrarily referred to the contractors calibration as a standard. They are presented in the following table for assumed values of the balance output.

| E gm | DIFFERENCE IN PERCENT OF FULL SCALE OUTPUT REFERRED TO CONTRACTOR CALIBRATION | | |
|---|---|---|---|
| | AFFDL (Vertical) | AFFDL (Horizontal) | r.m.s. Average |
| 0 | .010 | .003 | .002 |
| 1 | .012 | .072 | .020 |
| 2 | .013 | .140 | .055 |
| 3 | .015 | .208 | .057 |
| 4 | .016 | .276 | .075 |
| 5 | .018 | .344 | .094 |
| 6 | .019 | .412 | .112 |

In general, the difference is always less than one percent of full scale, with the greatest difference occurring at near full scale operation. The maximum difference occurs when the balance is used in its horizontal position. For E = 6 volts this difference is slightly below one half of one percent of full scale output.

An error analysis of the Preston tube skin friction coefficient by differentiation of the Preston tube equation can become tedious; therefore, the analysis presented in this report will be numerical in nature. Since all Preston tube equations are somewhat similar, the analysis will be carried out for the form given by Equation 17. The sample calculations will be referred to the measurement taken at station 1 where X = 28.68 inches for an edge Mach number of 2.90 and a momentum thickness Reynolds number of $2.0675 \times 10^4$. The corresponding Preston tube skin friction coefficient was 0.0012535 for the following test condition.

| $P_o$ | $T_o$ | $T_w$ | $P_w$ | $P_p$ |
|---|---|---|---|---|
| psia | °R | °R | psia | psia |
| 82.57 | 516.32 | 500.95 | 2.62 | 8.77 |



Assuming that all instruments result in correct data except the wall static pressure ($p_w$) transducer which now is 5% larger than 2.62 psia or 2.75 psia. Then a step-by-step calculation as described in Section IV of this report produces a skin friction coefficient of 0.0012033 which is 4.01% less than the reference value of 0.0012535. Still another example is to assume that the static (wall) pressure transducer is correct and gives a reading of 2.62 psia while the Preston impact transducer reads 5% too high or 9.21 psia. This leads to $C_f$ = 0.0011462 corresponding to a decrease of 8.56% in the skin friction coefficient. The results of various calculations are summarized in the following table:

| Percent Change | | |
|---|---|---|
| $p_w$ | $p_p$ | $(C_f)_{HK}$ |
| +5 | 0 | -4.01 |
| 0 | +5 | -8.56 |
| +5 | +5 | 1.12 |
| +5 | -5 | -9.19 |

According to the above table the greatest error in the skin friction coefficient (for this case only) is -9.19% and is the result of a + 5% error in the wall static pressure coupled with a - 5% error in the Preston tube impact pressure reading.

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# SUPPLEMENTARY

# INFORMATION

AFFDL-TR-79-3136 September 1980

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ERRATA - December 1980

The following corrections are applicable to AFFDL-TR-79-3136, "Skin Friction Measurements at a Mach Number of Three and Momentum Thickness Reynolds Numbers Up to a Half Million," UNCLASSIFIED report, September 1980:

Page 47

Change heading in column seven to read

$$VD_x\ 100$$

Page 50

Change Equation A.6 to read

$$\alpha = \frac{0.55484}{\sqrt{\sigma}} \sqrt{\frac{T_e}{T_w}} \sin^{-1} \sqrt{\sigma}$$

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AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433